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with which is incorporated The Institution of Aeronautical Engineers

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PROCEEDINGS

FOURTH MEETING, FIRST HALF, 66TH SESSION

The Fourth Meeting of the first half of the 66th Session of the Royal Aeronautical Society was held in the lecture theatre of the Royal Society of Arts, at 18, John Street, Adelphi, London, W.C.2, on Thursday, November 20th, 1930, when a paper on " Recent Developments in Engine Cooling," by Captain Andrew Swan, was read and discussed. The meeting was a joint one with the Institution of Automobile Engineers. Colonel The Master of Sempill (Past-President of the Royal Aeronautical Society) was in the Chair.

The PAST-PRESIDENT: He wished first of all to convey an apology from the President (Mr. C. R. Fairey) for his inability to attend, due to having been detained at an important technical conference at Rochester. He also conveyed apologies on behalf of the President and Vice-Presidents of the Institution of Automobile Engineers, who were engaged upon various duties connected with the Institution.

Speaking for the Royal Aeronautical Society, the Past-President said that its members considered it a great privilege to have the opportunity of meeting the members of the Institution of Automobile Engineers on two occasions each year for the purpose of discussing problems of common interest. The subject of Captain Swan's paper was of interest to both bodies. It was particularly so to the Royal Aeronautical Society, as it involved the all-important question of performance, and the increased and increasing performance demanded of road vehicles would make the subject of interest to automobile engineers.

Introducing Captain Swan, he recalled that he had served on the staff of the Air Ministry for nine or ten years, carrying out work on aero engines, and for the past three years he had been head of the Engine Department at the Royal Aircraft Establishment, Farnborough.

RECENT DEVELOPMENTS IN ENGINE COOLING*

BY

CAPTAIN ANDREW SWAN,

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Aircraft engines are classed as air-cooled or water-cooled, accordingly as they are cooled directly by contact with air or indirectly by air through the intermediary of the water which surrounds the cylinders. The method of cooling used has been a cause of wide divergence in design and arrangement between the two types. The air-cooled engine, except for the smaller powers, appears in the radial form in which exposure of each cylinder to the air stream is simplified at the expense, however, of a large frontal area while, with obviously

* Joint Lecture with Institution of Automobile Engineers.

greater latitude, the water-cooled engine can take a form having a smaller frontal surface.

The cooling in each type of engine is done by placing the cylinders or radiator in the stream and is obtained at the cost of a drag or resistance to the motion of the aircraft. It is clear that the drag should be a minimum consistent with adequate cooling. A streamline form is difficult to attain in radial engines and improvement towards reduction in drag is therefore being sought by fitting cowling to smooth out the air flow over the nose of the aircraft and at the same time direct air to the vital parts requiring to be cooled.

The water-cooled engine can usually be enclosed in a cowling of reasonably streamlined shape leaving the radiator as the only portion to cause appreciable drag. Means are also employed with radiators, as by making them retractable into the body of the aircraft, to reduce the exposed area and consequent drag to that only necessary for cooling under the condition of flight. Wing cooling of the water has also been used. In this system the water passes through tubes forming the surface of the wing or alternatively through a narrow space formed by a double skin fitted to the wing. Drag is thereby reduced, but the construction is not simple and in conjunction with the weight of water in the wing tends to structural heaviness.

The problem of effective cooling of an aircraft engine is therefore inseparably associated with the requirement of small drag and most of the work on engine cooling described in this paper had for its primary object the reduction of drag with, if possible, no detrimental effect on engine operation and no loss in cooling efficiency.

The developments to be described are, in general, applicable to all water or liquid-cooled engines and not confined to any one type as might be the case with experimental work on air-cooled engines where cooling is mainly dependent on a cylinder head form which may be and probably is peculiar to a particular engine.

Cooling an engine cylinder is necessary to ensure that it and the working parts in close contact with it do not become hot enough to cause distortion and also that a film of oil is preserved and not burnt off between the surfaces in contact. A very cool cylinder wall, however, would encourage deposition of the petrol and cause inefficient combustion. A high cylinder jacket temperature within the limits prescribed above would raise the temperature of the working cycle in the cylinder and would reduce the weight of air charge taken in and power output of the engine. It would also tend to promote detonation. Some measure of the effect of using a higher jacket temperature than is at present used would appear to be obtained from a comparison of air and water-cooled engines. The former operate at a higher mean temperature, and the advantage of power per unit volume is slightly in favour of the latter. This does not mean, however, that jacket temperatures substantially higher than are used in water-cooled engines may not be an advantage in view of the smaller radiator and reduction in drag made possible thereby.

Some Liquid Coolants Other Than Water

It has been suggested at various times that benefit would result from the use of a liquid coolant other than water which could be used at higher temperatures than are usual, and this possibility has been examined to a limited extent.

Any liquid to be used in this manner must have a boiling point above the temperature of proposed operation; should not have any deleterious effect on the materials used in the cooling system; be easily circulated by pump; have a flash point higher than the operating temperature and preferably a high specific heat.

The substances chosen for investigation at the Royal Aircraft Establishment were ethylene glycol and glycerine. There may be other liquids equally, or even more suitable for the purpose, but these substances were chosen because they

are readily available in bulk at a reasonable cost and have most of the properties required of a coolant.

A few approximate particulars of these liquids are given in Fig. 1 for comparison with those of water. Both ethylene glycol and glycerine have little or no deleterious effect on the metals used in radiator systems, although they deteriorate rubber slowly. Ethylene glycol is safe from ignition by flame if the liquid is at a temperature below 124°C., but at higher temperatures there is the possibility of fire through leakage or crash if brought into contact with flame. The spread of fire is rapid if the liquid is at a temperature above the flash point. Glycerine has a much higher flash point and it could therefore be used as a coolant at quite high temperatures without adding to the fire risk in aircraft. Both substances when at normal atmospheric temperatures will ignite if sprayed into a hot pipe at a temperature of 500°C. or above.

	Density at 25°C	Viscosity at 25°C	Spec. Heat	Boiling Point °C	Flash Point °C	Freezing Point °C.
Water.	1.0	1.0	1.0	100	-	0
Ethylene Glycol	1.11	17.0	.62	197	124	-17
Glycerine	1.26	600	.59	290	-	-
97% Glycerine	1.25	400	.59	-	178	

Some Properties of Liquid Coolants.

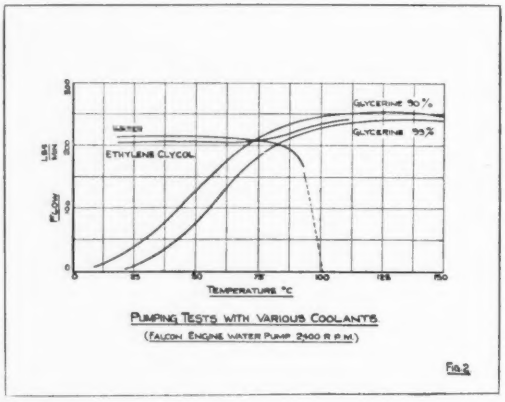
Fig. 1.

The boiling points of both are sufficiently high for the purpose in view. The specific heats are much lower than that of water, but in regard to the capacity to take up heat the effect of this is compensated for to some extent by a greater density. Actually for any given pump the circulation rates for these liquids at the high temperatures considered is greater than that of the corresponding water system, with the result that the temperature rise through the engine jackets is increased only a little in comparison with that of water circulation and not to the extent indicated by the relative values of the specific heats.

Although ethylene glycol has about 17 times the viscosity of water the rate of circulation by ordinary water pump is much the same as for water at the lower temperatures and continues to increase at temperatures above 100°C. when, of course, the circulation of water has ceased. Glycerine is very viscous at low temperatures and in a pure condition will not commence to circulate until 22°C. and then only very slowly. As the percentage of water is increased in glycerine the viscosity is reduced, and for a 90 to 93 per cent. concentration pumping can commence at −6°C. The curves of pump circulation against temperature of coolant are shown in Fig. 2.

As a coolant ethylene glycol is suitable particularly up to temperatures of 120°C. It can be used above this temperature, but this involves an addition to the existing fire risk in aircraft. Ethylene glycol is very " searching," and great care is necessary to ensure tight joints to prevent leakage. Pure or nearly pure glycerine is quite unsuited for the purpose, but if used at a concentration of 93 per cent. it can be circulated at low temperatures and is then suitable. Any water content evaporated at temperatures above 100°C. would require replacement unless condensed in the system itself. Should the demand arise it is probable that a derivative of glycerine of low viscosity and in other ways suitable could be made commercially for the purpose.

Some calibration tests of a standard engine with ethylene glycol as a coolant were made at a jacket outlet temperature of 150°C. As compared with the water-cooled engine the drop in power was some 7 per cent. With prolonged running, the high jacket temperature caused deterioration of the engine and the tests were discontinued. It is only reasonable to expect, however, that an engine developed to a fine pitch of efficiency under water-cooled conditions would require some development, may be only of a minor character, to withstand this higher temperature.



Against any drop in engine power there must be placed the reduction in drag due to a reduced radiator size. For any one form of radiator the surface required is dependent on the mean temperature difference between the coolant and the air, which for a coolant temperature of 150°C. is approximately twice that for normal water cooling. Also, direct cooling of the engine will be increased because of the higher operating temperature and the radiator will have less heat to dissipate and can be reduced accordingly. The reduction in radiator size should therefore be at least 50 per cent.

The reduction in drag becomes very important as aircraft speeds are increased, and it is estimated that at speeds above 150 m.p.h. the loss of engine power would be more than balanced by the reduction in drag. If, however, the engine power can be maintained the advantage is appreciable even at moderate aircraft speeds. For a supercharged engine operating under a coolant temperature of 150°C. any small loss in power could be restored without difficulty by a slight increase in supercharge, so that an aircraft thus fitted would have the benefit of reduced drag with no loss of engine power.

An operating temperature of 150°C. has been considered throughout, but of course any intermediate temperature between 100°C. and 150°C. could be used with advantage in control of jacket temperature at a constant value and

reduction in radiator size. The effect on radiator size is illustrated by Fig. 3 on which curves of mean temperature differences are plotted against altitude for coolants at constant temperatures of 150°C., 100°C. and for the normal water-cooled engine; the conventional standards of air temperature are used as a basis. The vertical intercepts of these curves represent in inverse ratio the relative radiator sizes required assuming the same form of radiator.

It is difficult to assess from the foregoing brief examination of the subject the relative merit of using high jacket temperatures, and further engine tests, particularly on several types of engines would be of value. From the limited data available, however, it appears that the advantages are not very marked unless means are taken, as in the supercharged engine, to restore the power loss likely to result.

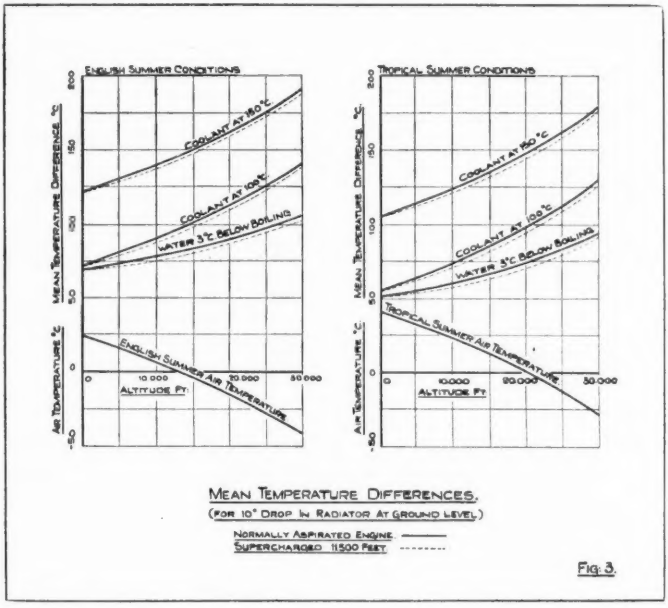


Fig. 3.

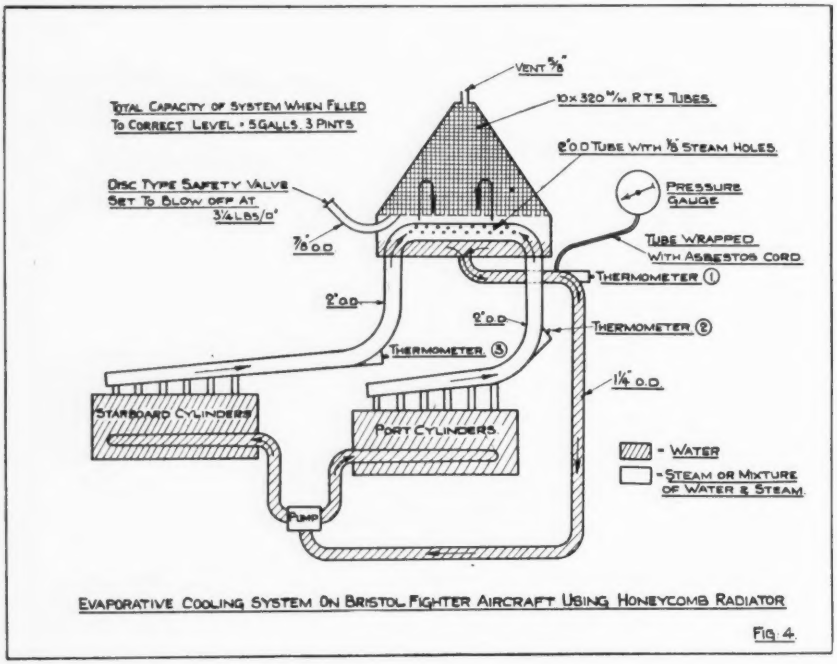
Before leaving this subject it may be of interest to mention that mixtures by volume of 30 per cent. ethylene glycol and 70 per cent. water and of 36 per cent glycerine and 64 per cent. water are now used in place of water to avoid freezing in the system under conditions of exposure to cold weather. Each of these mixtures will prevent freezing down to a temperature of -15°C.

The Evaporative Cooled Engine in Aircraft

In the evaporative-cooled engine the water in the cylinder jackets is converted into steam, and owing to the high latent heat of conversion a larger amount of heat can be absorbed per lb. of water evaporated than per lb. circulated by normal water cooling. With this method of cooling less water is required in the system and the temperature of the cylinder jackets is automatically controlled to that of the boiling point of water at the altitude concerned. The amount of water it is necessary to carry in an evaporative-cooled system is not, however, reduced in proportion to the increased capacity of the water to take

up heat as the amount of water required for the cylinder jackets and as a reserve against loss by evaporation and other causes is the determining factor.

Aircraft engines have been operated successfully at the Royal Aircraft Establishment and elsewhere under evaporative-cooled conditions. The chief danger anticipated was the possibility of local heating of the combustion head through the formation of steam pockets not swept away by the circulating water, and in the preliminary runs, without any alteration to the engines, much trouble was experienced with hot exhaust valves and gummed-up piston rings. These difficulties were thought to be due to unequal flows of water through the cylinders and tests were made to determine these flows. The tests showed that there was considerable variation of the water circulation to each cylinder and


VENT 3/8"
TOTAL CAPACITY OF SYSTEM WHEN FILLED TO CORRECT LEVEL - 5 GALLS. 3 PINTS
10 x 320 m/m R T 5 TUBES
2" O.D TUBE WITH 1/8 STEAM HOLES
DISC TYPE SAFETY VALVE SET TO BLOW OFF AT 3¼ LBS/0"
PRESSURE GAUGE
7/8 O.D
TUBE WRAPPED WITH ASBESTOS CORD
THERMOMETER (1)
2" O.D
2" O.D
THERMOMETER (2)
THERMOMETER (3)
1¼" O.D
STARBOARD CYLINDERS
PORT CYLINDERS
- WATER
- STEAM OR MIXTURE OF WATER & STEAM
PUMP

EVAPORATIVE COOLING SYSTEM ON BRISTOL FIGHTER AIRCRAFT USING HONEYCOMB RADIATOR

FIG. 4.

it is probable that with the formation of steam in the jackets the restriction in those cylinders with relatively small flows would be accentuated and overheating result.

Water flows to each cylinder, or to separate blocks of cylinders, as the case may be, were made approximately the same by modification of the inlet pipes and, in addition, the outlets were made larger so that the issuing steam carried with it as little water as possible. Piston and piston ring clearances were increased slightly and in one case gumming up of the rings was eliminated by a change from treated castor oil to standard P.4 mineral oil.

Endurance runs on the test bed were satisfactorily completed after these modifications had been made and the engines were calibrated for comparison with the powers obtained under normal water-cooled conditions. The loss of power was slight and in no case exceeded 2½ per cent.

As an intermediate stage before embarking on the full employment of evaporative cooling with wing condensers, an evaporative-cooled Falcon engine was installed in a Bristol Fighter for flight trials at Farnborough about three years ago. The aircraft was fitted with a special triangular steam condensing honeycomb radiator placed above the top centre section. Fig. 4 is a diagram of the system employed on this aircraft, and it will be noted that no steam separator was used although the condenser itself acted in this capacity.

General flight tests, climb tests and gliding tests were made and the cooling was quite satisfactory. There was no noticeable loss of steam and no evidence of any tendency to freeze in the radiator or its vent. The possibility of freezing in the upper passages of the radiator was tested by opening up after a long glide with engine running slowly. It was also separately examined on the test bench by supplying part of the radiator with steam while at the same time subjecting it to an air blast at temperatures down to $-15°C$. When a full supply of steam was turned on no excessive pressures were recorded, so that even if freezing occurred it caused no restriction.

The flight tests were intended to test the reliability of the evaporative-cooled engine, but at the same time it was possible to make certain deductions as to the practicability of the full scheme.

The temperature of the water out of the radiator was always some $5°C$. below the boiling point of water at the altitude of flight, so that appreciable cooling was by water cooling alone. On an average over the tests it was estimated that only a little more than half the cooling was evaporative. That a great proportion of the cooling was by normal water cooling was attributed to the large circulation and the absence of a steam separator. The radiator itself acted as a separator, but at too late a point in the circuit. A more efficient use of the system would therefore be obtained if a steam separator were fitted close to the exit from the jackets so that steam only would go to the condenser.

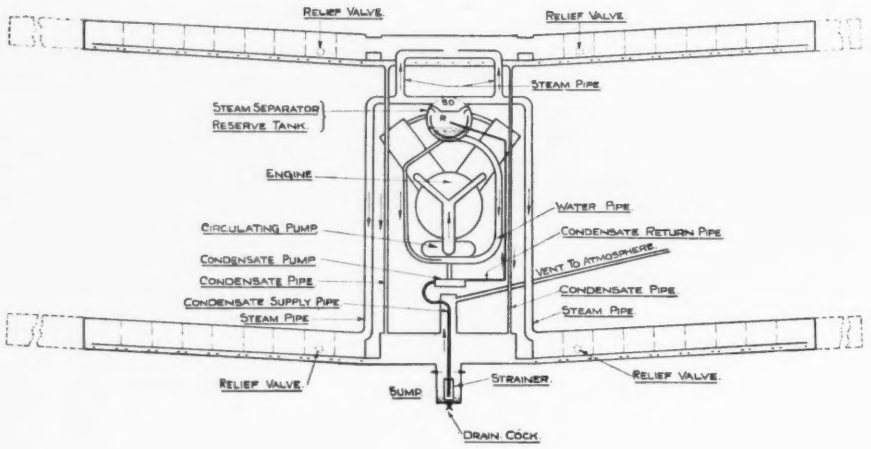
These are matters of considerable importance when considering the use of wing condensers, as it is very essential that the amount of water carried over with the steam be reduced to a minimum, otherwise there will be an excess of weight in the wing due to this water and also there is the risk of a large quantity of water being held in the condensers and so depleting the amount available in the jackets for cooling.

The final stage to establish the practicability of the system in aircraft was to utilise the wings themselves as condensers and so eliminate the drag of the honeycomb radiator used in the previous tests.

It was decided to make this further research on the same Bristol Fighter aircraft because so much experience had already been gained on the evaporative-cooled Falcon engine with which this aircraft was fitted. It was realised that the problem of providing sufficient condensing surface was made easier in this aircraft than it would have been in a modern aircraft, because of the larger wing surface available with respect to the horse-power to be dissipated and also that in an aircraft of greater horse-power loading per unit of wing surface the form of the condenser and its construction as a component part of the wing would involve new problems, which would, in fact, be largely peculiar to each type of aircraft. The experiments here described were therefore intended to supply fundamental data of the system in operation which would be applicable in general to all types of aircraft and to obtain experience, although limited, of some of the practical difficulties in its application.

Several schemes were considered before deciding on the one finally adopted and the selection of this was made because it could be applied to the Bristol aircraft without too serious modification and further because the particular form of condenser chosen had already been examined in the wind tunnel as to its cooling capacity and considerable data were therefore available.

The system as fitted is shown in principle on Fig. 5 and operates as follows: Steam and water from the top of the cylinder jackets pass to the steam separator placed in the vee of the engine and from there the steam flows simultaneously to each of the four condensers, two in the top wing and two in the bottom wing. The top wing condensers receive the steam at the centre section while the bottom wing condensers are supplied at the root of each wing, the bottom centre section being retained as a collector for the condensate. The water from the separator is returned by means of the usual circulating pump to the jackets and so a circulation is maintained which ensures freedom from steam pockets in the jackets. The condensate is returned to the separator by another pump.



DIAGRAMMATIC ARRANGEMENT OF CONDENSING SYSTEM FOR BRISTOL FIGHTER (FALCON III.)

FIG. 5.

The condensers are fitted in front of the main spar on a wing of R.A.F. 30 section and occupy the whole of the leading edge of each wing as far as the outer strut. This wing section allows the condensate to be drained to the lowest point at the bottom of the spar under all conditions of normal flying.

Fig. 6 is a photograph of the installation in the aircraft and the shape of the leading edge condensers, the position of the separator, and layout of the piping are clearly shown.

Mechanical tests were made on a specimen of condenser to ascertain its behaviour in the severest conditions of bending likely to occur in flight and later each condenser section was subjected to an internal and external pressure test of $1\frac{1}{2}$ lb. per sq. inch. Relief valves set to blow off at plus or minus 1 lb. per sq. inch were fitted to each wing condenser so as to provide for sudden generation or condensation of steam, but were found unnecessary as the air vent proved sufficient to prevent excessive pressure.

The separator was designed also to serve as the reserve water tank and is located in the engine vee below the standard engine cowling in place of the forward gun tube. It consists of a long cylindrical tank having 12 branches

arranged to correspond with the water outlet branches from the cylinders. The reserve water capacity is two gallons.

The condenser surface required to dissipate the heat was estimated from the results obtained from wind channel tests* of a similar section, due allowance being made for scale effect, air temperature and other factors. A further correction had to be made because it was proposed to use a smaller percentage of the chord of the Bristol Fighter wing than had been used in the model tests, and this correction, which was concerned with the distribution of heat emissivity over an aerofoil, was based on tests reported upon in R and M. 1163, "On the Convection of Heat from the Surface of an Aerofoil in a Wind Tunnel."

Thermometers were fitted at suitable intervals along each condenser with recording dials located in the cockpit, and these were used to indicate the progress of the steam along the wings and the distribution throughout the system.

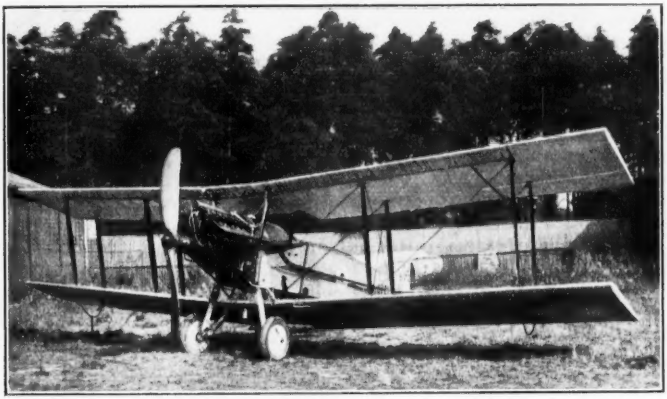


FIG. 6. *Crown Copyright Reserved.*

Bristol Fighter adapted for evaporative cooling.
Vickers-Potts oil cooler.

Some difficulty was experienced at first in securing equal distribution of steam as this varied between level flight and climb conditions, but eventually a sufficiently good compromise was obtained by fitting control ferrules in the main steam delivery pipes from the separator to each condenser.

The total quantity of water in the system is $4\frac{1}{2}$ gallons of which $2\frac{1}{2}$ gallons are required to fill the engine and its piping to the level of the bottom of the steam separator. The remaining 16 pints (measured cold) is the reserve water which, in the installation, represents practically that which can be lost without endangering the safety of the engine. The expansion of the whole when heated to the boiling point is some 4 per cent. or 1.4 pints.

Tests were made in which the whole condenser system was filled with steam by running up the engines on the ground and immediately shutting down; the quantity of water present in the condensing system on cooling was found to be $2\frac{1}{4}$ pints. It therefore appears that the nett reserve water is about 14 pints.

The first flight tests were made with the whole of the condenser surface in use and the water loss averaged slightly under one pint for a climb to 5,000 feet and a cruising flight of two hours' duration. With one bottom wing condenser

* R. & M. 1326. Wind Tunnel Experiments on Steam Condensing Radiators.

out of action the loss on climb was 1½ pints with a further loss of 1¾ pints per hour for a cruising flight of two hours (winter conditions). With both bottom wing condeners out of action the water loss on climb was excessive.

The small loss of water with all the condensers in action does not indicate insufficiency of cooling area as it is considered that some small constant loss by expiration or leakage is inevitable. Actually for English summer conditions the full surface could be reduced appreciably without increasing the loss beyond a reasonable limit, even although this would mean that at ground level the condensers were slightly smaller than absolutely necessary. For an unsupercharged engine as this was, the horse-power falls off with altitude and accordingly, as with water radiators, less of the condensers is required for cooling as height is gained.

A total of thirty hours' flying was necessary to complete the programme of tests and during this time no defects other than minor ones appeared. These were mainly small leaks in the condensers which were easily remedied and no further trouble arose.

The system also functioned satisfactorily with an anti-freeze mixture of 30 per cent. solution of ethylene glycol and water, although the operating temperatures were slightly higher than with water alone.

To obtain information regarding the effect of reduced water circulation the circulating pump impeller was removed, leaving only the bare spindle for driving the condensate pump.

Two flights to 7,000 and 10,000 feet, respectively, were then carried out under conditions, except for atmospheric temperature, comparable with the flights when using ethylene glycol solution. The behaviour on these flights was quite normal, the water loss, after making allowance for the different atmospheric temperature, being similar to that of the ethylene glycol flights.

The weight of the aircraft fitted with an evaporative cooled system was approximately the same as when fitted with the normal system.

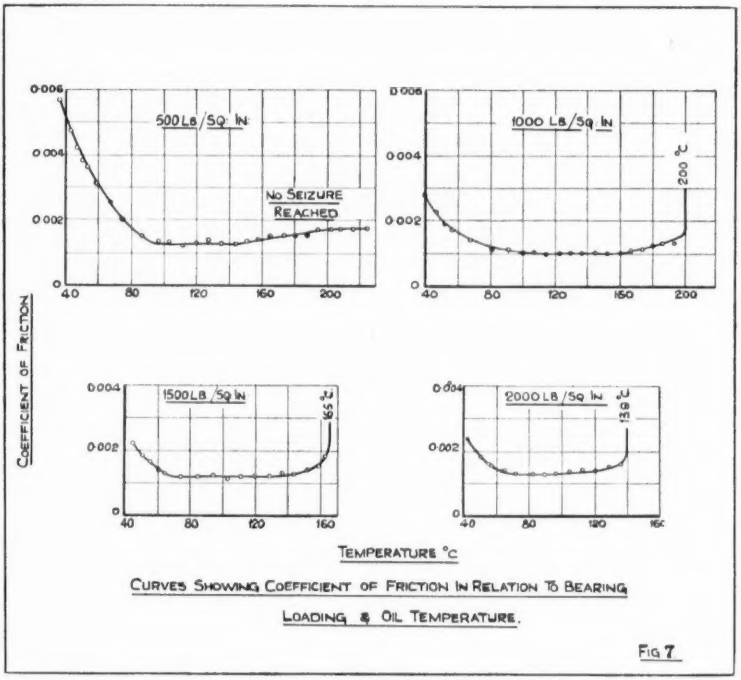
Experience gained with this installation and the consideration of other possible designs of condensers leads to the following tentative conclusions. The leading edge condenser occupying the wing in front of the main spar would appear to be restricted in its application to wings of comparatively small size and of large surface per h.p. In large wings the condensers would have a high volume to surface ratio, and cooling might be adversely affected. As the upper surface of a wing has good cooling properties for a considerable proportion of its chord, a condenser of low volume surface ratio could be obtained by using a double skin construction. Where, however, the area available is definitely limited, a retractable honeycomb radiator could be introduced into the circuit to assist under conditions of peak load.

Some Notes on Cooling the Oil

In aircraft it has become more necessary than previously to make provision for cooling the lubricating oil. This has probably arisen because engines are now more completely cowled in, and they, and the oil systems, are less exposed to the cooling airstream than formerly. Another contributing factor is that the power of engines has increased, not only in total output but also in horse-power per unit volume, so that the amount of heat transferred to the oil is increased with no corresponding enlargement of exposed surface likely to aid cooling. The cooling capacity inherent in all lubricating oil systems may then prove to be insufficient and an oil cooler become necessary.

it is generally accepted practice that the temperature of oil entering an engine should not exceed 70°C. The rise in oil temperature through the engine may vary considerably, depending on the engine, but it seldom exceeds 20°C. There is evidence that, as regards the load-carrying capacity of oil, higher temperatures could be used with advantage and it is worth while making a brief

examination of the possible effects of an oil circulation at higher temperatures. On Fig. 7 are shown representative curves obtained from National Physical Laboratory tests of permissible load against temperature for a bearing subject to centrifugal loading, and it will be noted that temperatures up to 120°C. could be used for any load likely to occur in aircraft engines. This temperature provides a considerable margin above the temperature of present practice, although it would be inadvisable to go so far as this on account of the possibility of higher temperatures occurring at local points. Difficulty might also arise when using oil at very high temperature and consequent low viscosity,



CURVES SHOWING COEFFICIENT OF FRICTION IN RELATION TO BEARING LOADING & OIL TEMPERATURE.

FIG 7

in ensuring that, in view of the increased leakage through bearings, each bearing receives an adequate supply. Any increase in the mean temperature of operation, however, would increase the mean temperature difference between the oil and the cooling air and would reduce the thickness of the cold viscous layer of oil on the walls of the cooler and so improve the cooling efficiency of the system.

As regards the foregoing it is interesting to record, although the tests were of too short a duration to be of any real value, that in the course of other work a radial air-cooled engine was run at full throttle for about an hour with an oil outlet temperature of 120°C. and later 150°C. for a shorter period. The condition of the engine, including the big-end white metal bearing, was excellent although it would be expected that at the higher temperature the white metal would show signs of softening.

The efficiency of an oil cooler placed in the air stream is dependent on the coefficients of heat transfer between the oil and metal and between the metal and the air. The latter coefficient, that between the metal and the air, should not vary very much in different designs of coolers if adequate contact of air and metal is ensured and fins be employed where possible to enlarge the area of contact.

The chief difficulty is to secure good transfer of heat from the oil to the cold metal because of the apparently inevitable formation of a relatively cold viscous non-conducting layer of oil in contact with the metal. For example, the heat transfer coefficient of a plain metal tube externally cooled and with hot oil flowing through it, is small because the flow takes the form of a core of hot oil with a considerable layer of cooled oil next to the metal. A large improvement in heat transfer can be obtained by making the oil passages of such form that scrubbing action on the internal surface takes place and the viscous layer of oil is reduced. This effect can be obtained in several ways, as by using a flattened tube twisted so that the path of the oil is continually being changed and impingement of the oil on the wall of the tube is obtained, or by

LABORATORY EXPERIMENTS ON HEAT TRANSFER FROM OIL TO METAL.

PARTICULARS OF TUBE.	OIL METAL CONTACT AREA. Sq Ft.	OIL FLOW. Galls / Hr.	MEAN VELOCITY. Ft/Sec.	PRESSURE DROP PER LENGTH. Lb/Sq In.	HEAT TRANSFER FROM OIL TO METAL PER Sq. Ft. PER 66·7 °C TEMP. DIFFERENCE. HORSE POWER.
PLAIN TUBE 24" LONG AND 0·44" BORE.	0·23	60	2·5	0·4	2·3
DITTO WITH SCREWS INSERTED EVERY ⅛ INCH.	0·32	60	-	2·3	12

THE MEAN TEMPERATURE OF THE OIL WAS KEPT AT 100 °C AND THE TUBE WALL AT 70 °C

THE TUBE WALL WAS TAPPED TO TAKE THE SCREWS THESE WERE SOLDERED IN POSITION, AND PROJECTED NEARLY ACROSS THE BORE OF THE TUBE

FIG 8.

placing obstructions in the path of the oil designed to produce the same effect. The improvement to be obtained is shown on Fig. 8. It will be noted that the rate of heat transference from oil to metal is increased by the screws in proportion to the increased pressure drop.

The several types of oil coolers in use have been fully described in Mr. Foord's paper read before the Royal Aeronautical Society (see R.A.S. Journal, December, 1929), but for the convenience of illustrating the difference in the designs and methods of operation employed, the Vickers-Potts and Carter coolers are shown in Figs. 9 and 10 respectively. In the Vickers-Potts type the oil is delivered by scavenge pump to a header and from there it flows simultaneously through each cooling element. These elements are of flattened elliptical shape and the design is conveniently arranged so that additional elements can be added if required. A spring loaded valve leading to a bye-pass circuit

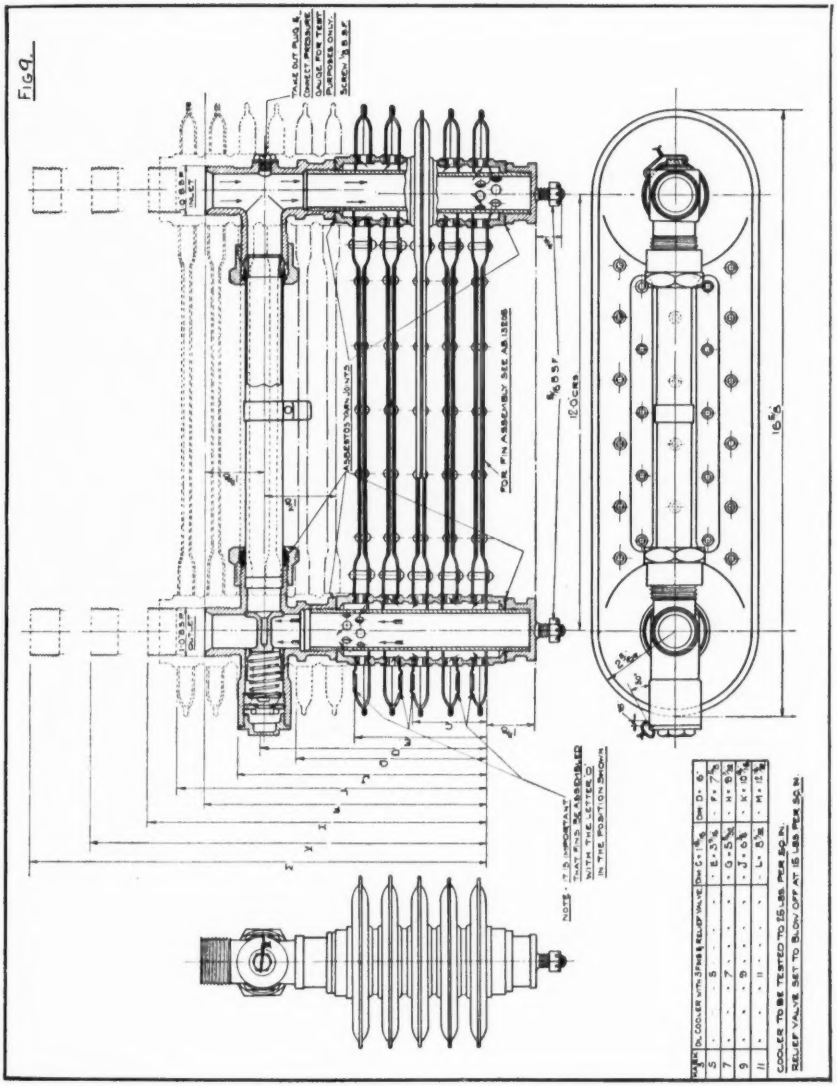


FIG 9.
TAKE OUT PLUG & CONNECT PRESSURE GAUGE FOR TEST PURPOSES ONLY. SCREW 1/8 B.S.P.
ADJUSTED DIM. 10.875
FOR FIN ASSEMBLY SEE AB.13226
16⅝
NOTE: IT IS IMPORTANT THAT END PLATE MARKED BOILER WITH THE LETTER O IN THE POSITION SHOWN
Dia. COOLER with 3 Nos RELIEF VALVE
Dim G ± 1/16
Dim D ± 0'
5 - - - - - E - 3⅛ - - F - 7⅛
7 - - - - - G - 5⅛ - - H - 8⅛
9 - - - - - J - 6⅛ - - K - 9⅛
11 - - - - - L - 8⅛ - - M - 12⅛
COOLER TO BE TESTED TO 15-185 PER SQ IN.
RELIEF VALVE SET TO BLOW OFF AT 15-185 PER SQ IN.

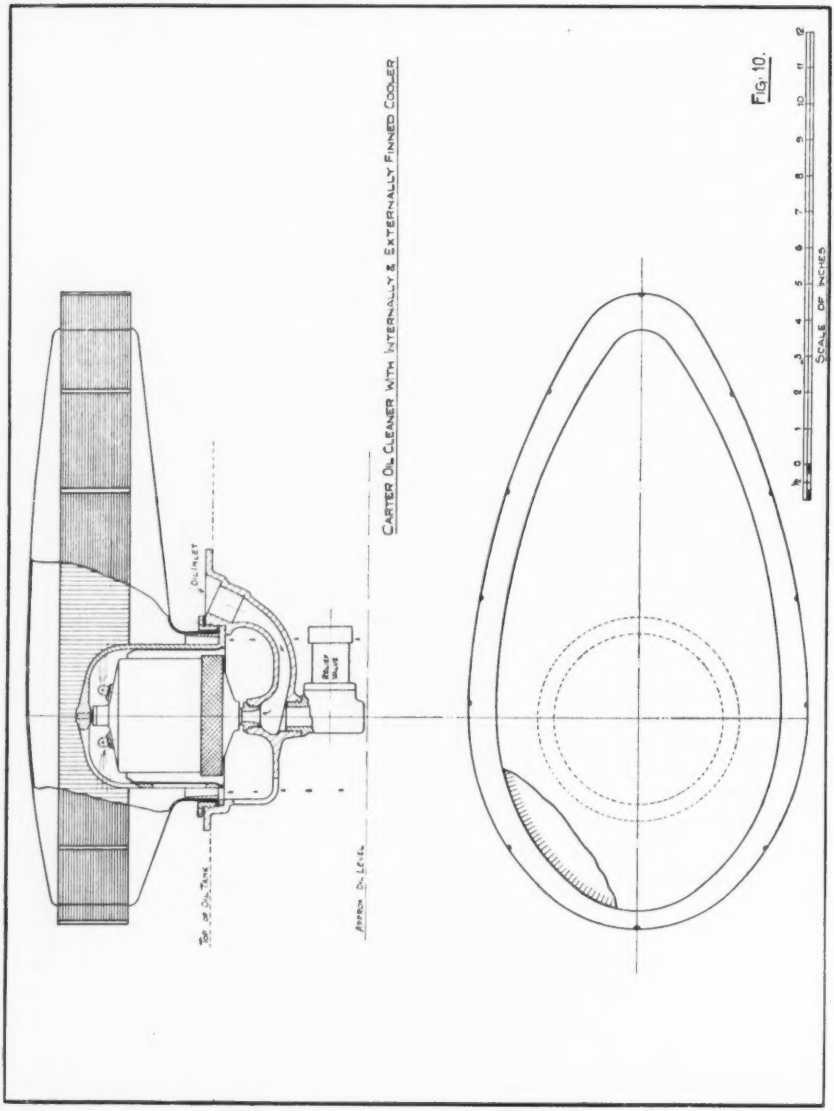

CARTER OIL CLEANER WITH INTERNALLY & EXTERNALLY FINNED COOLER
OIL INLET
RELIEF VALVE
SCALE OF INCHES

FIG. 10.

is included to come into operation when the oil is cold and high pressures are possible.

An entirely different method is used, however, in the Carter cooler shown on Fig. 10. The oil is sprayed on the inner surface of a hollow cooling element, placed in the airstream, and drains down this surface into the oil tank. A centrifuger, rotated at high speed by the reaction of the spraying jets situated at the top of the rotor, is incorporated for cleaning the oil and a relief valve discharging into the tank is provided for starting up. The cooling element is of streamline form and is provided with internal and external fins to give increased oil-metal and metal-air contact area, and thereby increase the cooling. It is not subjected to pressure and cannot become filled with congealed oil.

It is usually sufficient if an oil cooler reduces the temperature of the oil some 8 to 10°C., the remaining drop in temperature necessary and representing approximately half the total heat to be extracted from the oil being made in the oil piping and tanks.

The heat dissipating efficiency of a good oil cooler is estimated to be approximately 60 per cent. of that of water radiators and in consequence weight and drag are added which could be removed if the cooling were done more efficiently. In view, however, of the small amount of heat to be dissipated from the oil, namely, about 2 to 3 per cent. of the engine power and the consequent small size of coolers, the reduction in weight even with the best efficiency would be of small amount although not negligible. The drag imposed by a moderately efficient oil cooler at 100 miles per hour is quite small, but at 200 m.p.h. it becomes large enough to warrant attention being given to means for improving the cooling efficiency and design of the cooler. In the Schneider Trophy aircraft, in which drag had to be reduced to a minimum, the oil coolers were specially designed to fit in and to utilise existing surfaces of the aircraft without any addition to the drag. The coolers were designed to suit positions available in the aircraft and part of the cooling was obtained by passing the oil through flat rectangular tubes forming a skin on the fuselage and part by utilising the hollow fin as a cooling surface, the oil being sprayed over the internal surface of the fin by means of a number of small jets.

In conclusion, I wish to express my appreciation of the work of those members of the staff of the Royal Aircraft Establishment who carried out the experimental work described, particularly Mr. H. Wood and Mr. Anderton Brown, for their work on evaporative cooling.

Discussion

Wing-Commander T. R. Cave-Browne-Cave (Member of Council): Captain Swan had said verbally a good deal more than was printed in the paper concerning the necessity of eliminating air from the evaporative system, and expressed the hope that the paper, as published in the Society's journal, would contain the additional remarks, because his own experience indicated that the really important matter in connection with a condensation system was to ensure the elimination of air. The presence of air decreased the rate of condensation greatly. If one visualised steam in contact with a surface on which it was to be condensed, one could realise that the presence of any air in the steam not only diluted the steam in contact with the surface, but formed an air blanket which had to be swept away because whereas the steam condensed and disappeared the air did not. An additional point which was worth remembering was that steam condensing on a surface need only move at right angles to that surface as it then virtually disappeared; it was not necessary to produce a flow of steam over a condensing surface in the same way that it was necessary to produce a flow of hot gas over a cooling surface.

In airship work the triangular radiator had been evolved, and the Royal Aircraft Establishment had very wisely started from that experience and used a triangular radiator on the Bristol fighter before using wing ducts. The diagram Captain Swan had exhibited of the triangular radiator on the Bristol fighter suggested to him the reason why the Royal Aircraft Establishment had found so much water cooling in addition to evaporative cooling. The arrangement whereby the water was discharged into the tank of the radiator appeared certain to throw a great deal of the water on to the honeycomb which was intended to condense the steam. If the tank of the triangular radiator were properly shaped and the discharge suitably arranged, it could be made to act quite satisfactorily as the only separator required. The importance of the elimination of air was the reason why the triangular radiator was adopted; if one used a rectangular section and put steam in at the bottom, an air-lock was very probable.

The arrangement of the baffles in the wing condensing ducts was for the same reason and was of vital importance, particularly in connection with ducts in large wings. Captain Swan had suggested that in ducts in large wings it might be worth while to have a comparatively small steam space, formed by the outer surface and an additional inner skin. Such an arrangement would be heavy and would lack the advantage which the large volume afforded as a reservoir. With a very large wing the capacity in the steam space was such that the engine could run for a considerable length of time—quite possibly sufficient to get a big boat off the water or to achieve a reasonable climb—before the volume of steam made was sufficient to fill the duct independent of condensation. The volume available for the steam, therefore, constituted a very valuable reserve. The only objection to using a big volume of steam was that there might be difficulty in sweeping the air out, and that therefore the surface might be inefficient for a time and cause a considerable amount of steam to be lost from the vent. But if the baffles were properly arranged and the area for flow through the baffles properly graded, all experience so far available showed that the air would be eliminated satisfactorily. Captain Swan's statement as to the extraordinarily sharp definition of the boundary between the hot part and the cold part of the ducts confirmed this and showed that the principle—which was quite simple—was correct.

With regard to the application of evaporative cooling to the engines of the R.101, there was little to add to what he had described in his lecture to the Society in November, 1928, on the machinery installation of that airship. The water pumps had been eliminated from the Tornado engine. The new compression ignition auxiliary engines also worked on evaporative cooling and without water pumps. The experience of evaporative cooling in R.101 could be summed up by saying that they had had absolutely no trouble with it, and had used nothing else.

One of the advantages of the application of evaporative cooling in aircraft was that it provided an ideal system for heating passenger accommodation. Steam had been taken very considerable distances to heat the passenger accommodation and the system had proved simple and very effective. He could not help thinking that this would also be an ideal method of heating road passenger vehicles. It would be safe and radiators could be placed exactly where they were wanted. The amount of steam available would be much more than could possibly be required.

There had been considerable difficulty with oil-cooling in the Tornado engine because a very large amount of oil was circulated, and consequently, a very large amount of heat was taken up in the oil. In order to overcome that difficulty it was necessary to provide three times the oil-cooling area that was found to be satisfactory for a Condor engine. To avoid this weight, drag and complexity experiments had been made with what was described as "crankcase oil-cooling." The air required for combustion in the cylinders was drawn through the crank-

case, and passed through a simple separator to prevent oil being carried over into the cylinders. That system was extremely effective, because it brought air actually into contact with the oil, and cooled it directly. It also cooled the bearings and the surfaces which were heating the oil. The system was so effective that, in the engine which required three times as much cooling capacity as the Condor, it was found that by taking half the air required through the crankcase no external oil-cooling was necessary. They had found some initial trouble in preventing loss of oil, but when the right method was found it proved simple and very effective. The system was not installed in R.101 because when the installation was partly made somebody who was perhaps extremely cautious had remembered hearing of some crankcase explosion, and had raised objections on that score. The only crankcase explosions which he had been able to trace were in connection with petrol engines, or irrelevant for other reasons. He would be very grateful to have any authentic information which might bear on the safety of crankcase oil-cooling which appeared so attractive. It seemed, from what Captain Swan had stated, that it was really important that the oil suppliers should endeavour to provide an oil which would work satisfactorily at a somewhat higher temperature than at present. If an inlet temperature of, say, 110°C. could be used, then unquestionably the proper means of cooling the oil was by water. Cooling would then be easy because the cooling surfaces would never be so cold as to be clogged with viscous oil. Captain Swan had said that the cooling required for the oil was only 2 or 3 per cent. of the jacket heat; therefore, if the oil heat could be transferred to the water satisfactorily, it would only involve an increase of radiator size by a nominal 2 or 3 per cent.

Major T. M. BARLOW (Member of Council, Chief Engineer, Messrs. Fairey Aviation Co. Ltd.) : Unfortunately, perhaps, by reason of the fact that Captain Swan was engaged at the R.A.E., Farnborough, he had not been able to do full justice to the problem of evaporative cooling; naturally, he had confined himself to the work done at Farnborough, and had not been able to give information on the work done outside official circles. One gathered from the paper that a practical solution, on an engineering basis, of evaporative cooling as applied to aircraft had not yet been reached. That was not the case, however, for there was in existence a practical system of evaporative cooling for modern aero engines. In this respect, a few words on this system, developed by the engineering department of the Company with which he was associated, were considered appropriate.

Some two years ago the matter was discussed with the then Director of Technical Development and his (Major Barlow's) Engineering department was instructed to proceed with the development of such a scheme, bearing in mind that it had to apply to modern aero engines and aircraft. The research and development work was divided into four sections. In the first place, the engine to be used (a Rolls Royce " F " type) was subjected to Bench tests extending over a period of about 100 hours, and during the whole of that time only steam or evaporative cooling was used, records of flows, temperatures, and so on, were taken. In this stage no attempt was made to deal with the steam. In the next stage of the work the question of a suitable separator was solved. Naturally, it was so designed that it could be housed under the cowling of the engine, in order to avoid increasing head resistance. In the third stage of the development there was reproduced in the test house the exact installation as it would be fitted in the aircraft complete with condenser cooled separately by slipstream of propeller from another engine. In the fourth stage the installation as tested in the test house was transferred to a Fox aircraft (a High Speed Day Bomber), for complete flight tests. Flight tests had been carried out with that machine to date to the extent of about 15 hours.

Discussing the special conditions applying to any evaporative cooling system.

for application to aircraft, he said that in the first place the equipment must be lighter than that of a water system of cooling. The design of installation he had referred to was about 100 lbs. lighter than the equivalent water cooling system but he saw no reason why, by further refinements in design and starting *ab initio*, a saving of 150 lbs. should not be effected in an evaporative cooling system as contrasted with a water cooling system. Secondly, head resistance must be reduced to a minimum. Reference had been made by Captain Swan to the use of an adjustable or fixed honeycomb radiator as a condenser, but that should be avoided because it resulted definitely in increased head resistance. Condensers must be designed so that they afforded the minimum resistance, and so that they could be easily maintained, and repaired if necessary. The Wing type has many objections, size and weight and maintenance, besides being complicated for drainage, and for folding wing aircraft.

With regard to flight trials, he did not think a system could be considered satisfactory to lose a pint of water during a flight of two hours as described in the lecture. There should be no loss of water under all normal flying conditions—when climbing, when flying at level speeds and when carrying out ordinary manoeuvres. His engineering experimental department had carried out aerobatic flight tests for 30 minutes, continuous rolling, spinning, looping etc. with a loss of 2 pints only. The other tests done included full load climbs to heights of 18,000 feet with temperatures as low as $-27°$, giding tests (from heights), and in every case the engine temperatures had, on these latter tests, remained at from 85° to 90°, so that the engines could be opened up immediately.

Referring to the water capacity of the system described by Captain Swan, he considered this was capable of improvement. The system he used involved carrying 6 gallons only, 4 of which were in the engine; of the remaining 2 gallons, 1 was a reserve.

Finally Major Barlow again emphasised that evaporative cooling was an accomplished fact for aircraft engine installations on sound practical engineering lines and would appear to offer many advantages over water-cooled or mixture cooled systems especially for Service aircraft.

Mr. A. F. Evans (Institution of Automobile Engineers): Had the authorities contemplated the use, in the compression ignition engine, of a combined system whereby the cylinder walls were cooled in the ordinary way and the temperature of the combustion chamber was maintained as high as possible by means of steam? With regard to oil cooling, he had found that the most effective medium was the Royle tube, which was constructed in such a manner that the surface of the oil passing through it was broken up.

Replying to the request made by Wing-Commander Cave-Browne-Cave for information concerning crank chamber explosions, he referred to one explosion which had occurred in an experimental M.A.N. engine of 1,000 h.p. per cylinder. In this case a valve was accidentally tripped through a bolt falling on it, so that the flame was allowed to pass through into the scavenging belt, and the whole scavenge system had blown up. Another explosion had occurred on an ordinary four-cycle ship's Diesel engine where one of the timing gears heated on its spindle which had fired the mixture of lubricating oil vapours in the crankcase chamber.

Major F. M. Green (Messrs. Armstrong-Siddeley's): In 1915 or 1916 experiments were made at Farnborough with a cooling liquid known as "aniline" which boiled at a much higher temperature than water. An engine was run at a temperature of about 140°C. Aniline was expensive, however, and was not very satisfactory, because it gradually changed its composition when heated. He could not at all agree with Captain Swan's statement that the loss of engine power due to running an engine hot could be made up by increased supercharging.

It it were permissible to do this with a hot engine, then it would do equally well with an engine running cooler.

Captain Swan had said that a loss of 7 per cent. of horse-power caused by running an engine at 150°C. was made up by the decrease of drag on an aeroplane flown at 150 miles an hour or more, because the radiator drag was halved. This appeared to indicate that the radiator drag of an average aircraft at 150 miles an hour absorbed 14 per cent. of the horse-power of the engine.

Referring to Captain Swan's mention of oil temperatures as high as 150°C., he pointed out that the temperature of the cylinder wall on an aircraft engine was likely to be at least as high as this in ordinary running.

There seemed to be a property of oil which could best be described as "oiliness," of which there did not seem to be any exact definition. It was not the same as viscosity and was a property which vegetable oils seemed to possess in a greater degree than mineral oils. Could the author give any information on the effect of temperature on the various qualities of oil in this respect?

Mr. ALEXANDER DUCKHAM: With reference to the successful use of an emulsion of oil and water as a lubricating and cooling medium, he recalled that in 1906 Messrs. Yarrow and Co., rather in advance of the times, had built a 1,000 h.p. motor boat with an aluminium hull, but had experienced trouble in regard to lubrication, the pistons being distorted. He had been given an opportunity to investigate the matter—thanks to Sir Arthur Yarrow's unfailing kindness to young men—and, after careful laboratory work, had decided to recommend the use of an emulsion of oil and water. To his trepidation the recommendation was acted upon, but fortunately, the subsequent trials were absolutely successful. Mr. Duckham emphasised that, in gauging the capacity of an oil, or any fluid, as a cooling medium, one must not be led astray by examining merely its specific heat. Results he had obtained were extraordinary. In a comparative testing the cooling effect of water was measured as 2,100 calories; the cooling effect of oil was 1,010 calories; a half and half emulsion of the oil in water had a cooling effect of about 1,500 calories; and the emulsion of water in oil had a cooling effect of only about 1,100 calories. Thus, oil in a vehicle of water had a much greater cooling effect than water in a vehicle of oil, and that fact was worth remembering.

He joined issue with Captain Swan that oil, when passing through a cooler tube, inevitably formed a relatively cold, viscous, non-conducting layer of oil in contact with the metal. That would be so if the stream of oil moved slowly, but it was well known to those concerned with turbines that, if the velocity of the oil stream were increased, turbulence occurred. Thus, instead of there being a stream of hot oil flowing through an insulating layer of comparatively cold oil, there was turbulence and no layer. That could be demonstrated in the laboratory by introducing a very fine stream of highly coloured oil in the centre of a stream of pale oil flowing through a glass tube; when a certain critical velocity was reached, the thread of highly coloured oil no longer remained quite separate and distinct from the pale oil, but became mixed with it as the result of the turbulence.

Referring again to turbine practice, he pointed out that the turbine cooler lost its efficiency because of the chemical changes which occurred in the oil. The oil became oxidised, so that sludge and a certain amount of gum were formed. These bodies adhered to the surfaces of the tubes, and it was found, in the case of a turbine running with a bearing temperature of 140° F., for example, that when the cooler had been cleaned—this was best done by chemical means—the bearing temperature would fall to 110° F.

Colonel FELL (Messrs. Rolls Royce, Ltd.): In commenting on a statement in the paper that "it was reasonable to expect that an engine developed to a fine pitch of efficiency under water-cooled conditions would require some development,

though maybe only of a minor character, to withstand the higher temperature permissible when using ethylene glycol as a coolant," he asked what Captain Swan had in mind when making that statement. When designing a water-cooled engine, he said, if one wished to take full advantage of what water cooling would do, one designed for maximum compression ratio, and obtained the maximum cylinder output per unit of capacity that could be obtained with the maximum economy. The limiting factor was really the temperature of the combustion chamber walls, and it was difficult to visualise anything that could make it any better. For example, the Rolls Royce racing R engine was tried with ethylene glycol as a coolant, and it was found that it would be necessary to decrease the power quite considerably if higher wall temperatures were to be used.

With regard to oil cooling, he asked if Captain Swan had any figures indicating the effect of cooling the sump of an engine direct. It seemed that constructors, in order to obtain a fairly good streamline, went to a great deal of trouble to cowl in the sump of the engine on the inside of which the oil was spread in a very finely divided state; then they put outside the cowling a very much less well streamlined oil cooler, through which the oil had to pass, when it was not in a finely divided state and therefore much more difficult to cool. Some time ago he had been shown an oil cooler, the Stancliffe, which consisted of a tube having inside it a mechanically-rotated vane; the vane scraped the walls of the tube, and the efficiency of the cooler was very high indeed. He asked if Captain Swan had experimented with that cooler.

Although Wing-Commander Cave-Browne-Cave had achieved considerable success with the direct cooling of oil, Colonel Fell suggested that probably that system would not be applicable to, say, a small twelve-cylinder " V " engine, in which the crankcase dimensions, or the volume of crankcase per h.p., was very much less than was the case in the engine with which Wing-Commander Cave-Browne-Cave was experimenting. He believed that it would be almost impossible to separate the oil from the air under those circumstances, but asked for Captain Swan's views on that matter.

Finally, in reference to evaporative cooling, he said it seemed certain that the present-day type of water-cooled engines would all be evaporatively cooled within the next two or three years.

Major G. P. Bulman (Member of Council, Assistant Director, Engines, Air Ministry): He had hoped that the automobile engineers would have taken a greater part in the discussion since, in his view, aircraft engineers were perhaps rather apt among themselves to run round in circles and might learn a great deal from the criticisms and suggestions of other engineers. He had hoped, for example, to have heard something of the experience derived with the Rushmore car, on which he believed a good deal of work had been done with steam cooling.

Captain Swan's paper seemed to support the adage that one can never get anything for nothing. Attractive new ideas were brought up and research very properly applied to establish the facts—at Farnborough, he submitted, with discretion, skill and enthusiasm—but when that research had established the data, decision had to be made as to what overall advantage is to be gained by the application of these new developments. That judgment must now be applied to the development of evaporative cooling. It offered certain advantages and certain disadvantages and there would probably be need for compromise as between maximum reduction of drag on the lines of the Farnborough wing condenser and the greater practicability, at the expense of a little extra drag, on the lines referred to by Major Barlow. Incidentally he expressed gratitude to Major Barlow for having disclosed, he believed for the first time anywhere, the very promising results obtained with the installation to which he had alluded.

It must always be borne in mind that aircraft development was required

to produce apparatus which would not merely run admirably and with high efficiency in a laboratory or at an experimental station, but something of increased efficiency which could be placed in the hands of more or less ordinary men and used in all parts of the world without the constant attention of specially skilled personnel. On that score he personally believed that steam cooling had the advantage over the use of ethylene glycol, although curiously enough ethylene glycol seemed to be in active development in America to the exclusion of steam cooling, a selection which might or might not be due to the very active propaganda launched in favour of ethylene glycol.

In regard to oil cooling, he differed with Captain Swan's point of view. Certainly if oil temperatures were higher, cooling was more easily effected by virtue of the greater temperature gradient. Surely, however, we should not seek to employ hotter oil in order to cool it more easily, but work in the opposite direction in the endeavour to produce engine installations which produced such oil temperature rises as required the minimum of cooling. Captain Swan had suggested that the average temperature rise was of the order of 20° C. but in some actual cases the rise had been almost double that figure. A reduction, however, to 20° C. had been quite easily secured by reducing the total quantity of oil circulating through the engine, splashing about, and picking up heat. It was true that by picking up heat the oil helped to cool the engine but on the whole the increase in cylinder temperature caused by the lack of this cooling effect was not, he thought, so important as compared with the reduction in oil cooling difficulty which resulted.

With regard to Captain Swan's reference to the National Physical Laboratory tests showing the high temperatures at which bearings at certain pressure loadings can be run, it must be remembered that the oil outlet as normally measured and recorded obviously does not represent the temperature of the hottest points in the engine but is an average, and allowance must, therefore, be made to secure a reasonable margin. Whereas, too, Captain Swan had stated that the temperature of oil leaving the engine was generally of the order of 70° C., Service practice accepted a temperature more of the order of 95° C.,—a figure it is not proposed to exceed.

Mr. CHATTERTON (Institute of Automobile Engineers): From the motor car point of view, he said he did not see that the evaporative cooling, ethylene glycol cooling, or any alternative system had any advantage over the water-cooling system. He was not interested in reducing drag on the motor car, and reduction of drag seemed to be really the only advantage claimed concerning aircraft. He asked Captain Swan if he could see any real reason why an automobile engineer should consider departing from the water-cooling system.

On the question of cooling generally, he asked whether any consideration had been given to the combination of two systems of cooling. It seemed to him that, having regard to the present construction of an engine of the high efficiency type, in which the valves were all carried in the cylinder head, the part of the engine which required cooling mostly was the cylinder head, and that the cylinder barrel did not require such efficient cooling as did the head. Would it not be possible, therefore, to air cool the cylinder barrels and to cool the valve gear and cylinder head by either water cooling, evaporative cooling or one of the other forms of cooling mentioned by Captain Swan? It seemed to him that if that were done the amount of water or other liquid to be carried could be reduced; it would certainly simplify the piping difficulty, because it would probably enable the water or other liquid to be carried in one casting only, and it seemed that it would simplify the construction of the engine. That would allow of such a construction as was used normally in the air-cooled engine, but at the same time would give the advantage of liquid cooling of the valves. He asked Captain Swan whether he had any figures showing the

efficiency of oil coolers plotted on the basis of the temperature difference between the oil inside and the air outside—or for a constant oil temperature inside and varying air temperatures outside? It seemed to him that there should be a critical temperature of the cooling air at which the cooling efficiency would be a maximum, because although the cooling efficiency increased as the outside air temperature was reduced, the formation of the thick film of oil on the insides of the tubes increased, so that the degree of insulation from the cooling effects was becoming greater as the air temperature was reduced. He would like to know if that were so in practice, or whether his idea was incorrect.

Mr. W. O. Manning (Member of Council): Was there any alteration of the thermal efficiency of an engine when using ethylene glycol? He would also like to remark upon the fact that, although they had reached the 20th century, they were still discussing how they could ensure that 50 per cent of the power of the fuel used could be put into an engine.

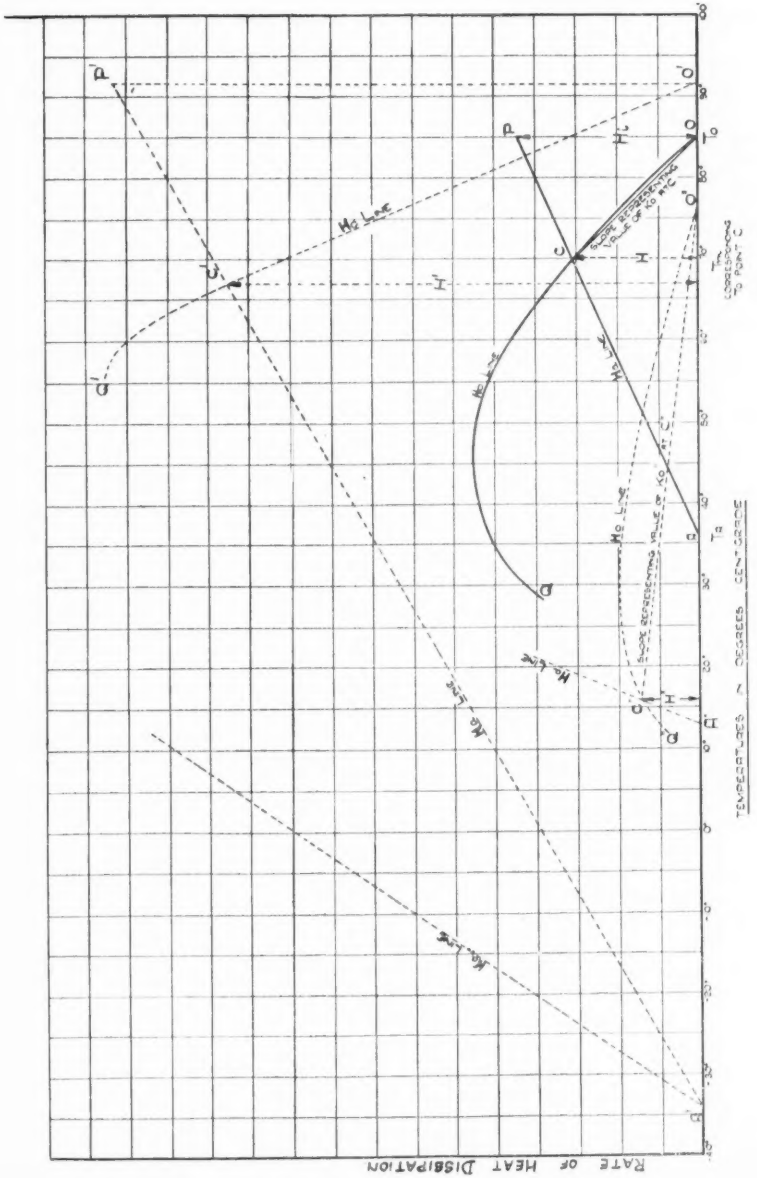
Mr. McLellan (Institution of Automobile Engineers): He disagreed with Mr. Chatterton's suggestion that automobile engineers would not gain advantage by departing from water cooling. He recently returned from India, where the Indian Army was experiencing considerable difficulty in obtaining lorry engines which would not lose a lot of water under the very arduous conditions in which they operated. For instance, vehicles used on the North-West frontier had to climb to an altitude of anything up to 8,000 ft., and to plough their way through deep sand, and if the adoption of evaporative cooling would enable the vehicles to operate without loss of water, it would be a very great advantage there. Discussing crankcase explosions, he recalled such an occurrence in an Air Force lorry, due, he believed, to the cylinders, pistons and rings being very badly worn so that they allowed liquid petrol to get into the crankcase. He could not say what was the actual cause of its ignition.

A Speaker: It seemed to him that the paper dealt more with engine heating rather than engine cooling. The aim seemed to be to ascertain how high the temperature around the engine could be raised. A point which should be taken into consideration by those concerned with research on air-cooling systems, was that the timing of the engine, or the magneto timing at any rate, varied as much as 60 per cent. for the same piston speed per minute. They must find out how far engine heat was produced by irregularities in design or manufacture. With regard to liquid-cooled engines, he suggested that Captain Swan might test out the results obtained with a mixture in the proportion of 1 lb. pure honey to one gallon of water. That mixture—which might be useful in motor-car engines as well as in aero engines—would withstand temperatures as low as 18° below freezing point; at the same time, it might also enable engines to be run at higher temperatures than those attained when water cooling was used.

Major B. C. Carter (Senior Scientific Officer, R.A.E.) (*contributed*): During the verbal discussion, he had described a form of graph which is helpful in dealing with oil-cooling problems. Such a graph is shown in Fig. 1

The base represents temperature and ordinates represent rates of heat transference. Consider an oil cooler that has attained steady conditions in an air stream at temperature *Ta*. Let *To* denote the mean of the inlet and outlet oil temperature, *Tm* the mean temperature of the walls of the cooler, and *H* the rate of heat dissipation. Then a metal-air temperature difference $Tm - Ta$ causes heat to be transferred from metal to air at rate *H*, and an oil-metal temperature difference *To-Tm* causes heat to be transferred from oil to metal at the same rate *H*.

For a given air density and state of air flow, the rate of heat transference from metal to air is proportional to temperature difference, and thus the ordinates of


RATE OF HEAT DISSIPATION
TEMPERATURES IN DEGREES CENTIGRADE
Mg Line
Mg Line
Mg Line

the straight line ACP give this rate of transference for any metal temperature when the air temperature is Ta.

Similarly, some line OCQ represents the rate of heat transference from oil to metal for any metal temperature when the mean oil temperature is To, but, in general, this line is not straight although it is approximately so near the point O. The form depends among other things on whether the change of Tm occurs with constant oil flow or with constant pressure drop across the cooler.

If the heat transference from oil to metal is improved by some means, as by increasing the turbulence of the oil, the slope of OC will be increased and the intersection point C will move nearer to P. Thus Tm and H are increased. It is clear, however, that no such improvement can increase H beyond the value $Op = Hi$ for the same air flow conditions. Thus Hi represents the ideal attainable and, from this standpoint, the efficiency of the cooler may be regarded as H/Hi. This is equal to $(Tm - Ta)/(To - Ta)$, so that the more efficient the cooler, the nearer is the metal to the mean oil temperature.

When water is circulated vigorously through an oil cooler, the metal temperature is not appreciably lower than the mean water temperature, and hence, by making a test using water instead of oil under the same air flow conditions, the value of OP may be determined and the line ACP drawn. Alternatively, it may be possible to infer the slope of the line ACP for a given cooler from existing knowledge of the transference of heat from a surface to air flowing past it.

The value of Tm and the slope of OC for any particular oil flow conditions may be found by measuring H and finding the point C on ACP, that is, at height H above the base.

The effect of increasing the air speed or the air density is to increase the slope of ACP and to move the intersection point C towards Q. This increases Hi, and H is increased also within a limit depending on curve OCQ. The process decreases the efficiency of the cooler unless steps are taken to improve the curve OCQ.

By representing the matter graphically in this way, the effects of changing the conditions of operation of a cooler may be studied and predicted if sufficient is known concerning the laws governing metal-air and oil-metal heat transference.

By way of example, lines $A'C'P'$ and $O'C'Q'$ have been drawn to indicate the greatly increased heat transference rate H' resulting from a lower air temperature Ta' at about the same air density and speed combined with a higher mean oil temperature To' and an improved coefficient of heat transference from oil to metal. Again, lines $A''C''$ and $O''C''Q''$ represent the much lower rate of heat transference resulting from a very poor oil-metal heat transference line. Although $To'' - Ta''$ is greater than $To - Ta$ and the slope of $A''C''$ is much greater than that of AC, the heat transference rate H'' is much less than H. The heat transference would be greater if the slope of A″C″ were reduced, within quite a wide limit. For such an over-cooled cooler there is great scope for improvement of performance by improving the oil-metal heat transference coefficient.

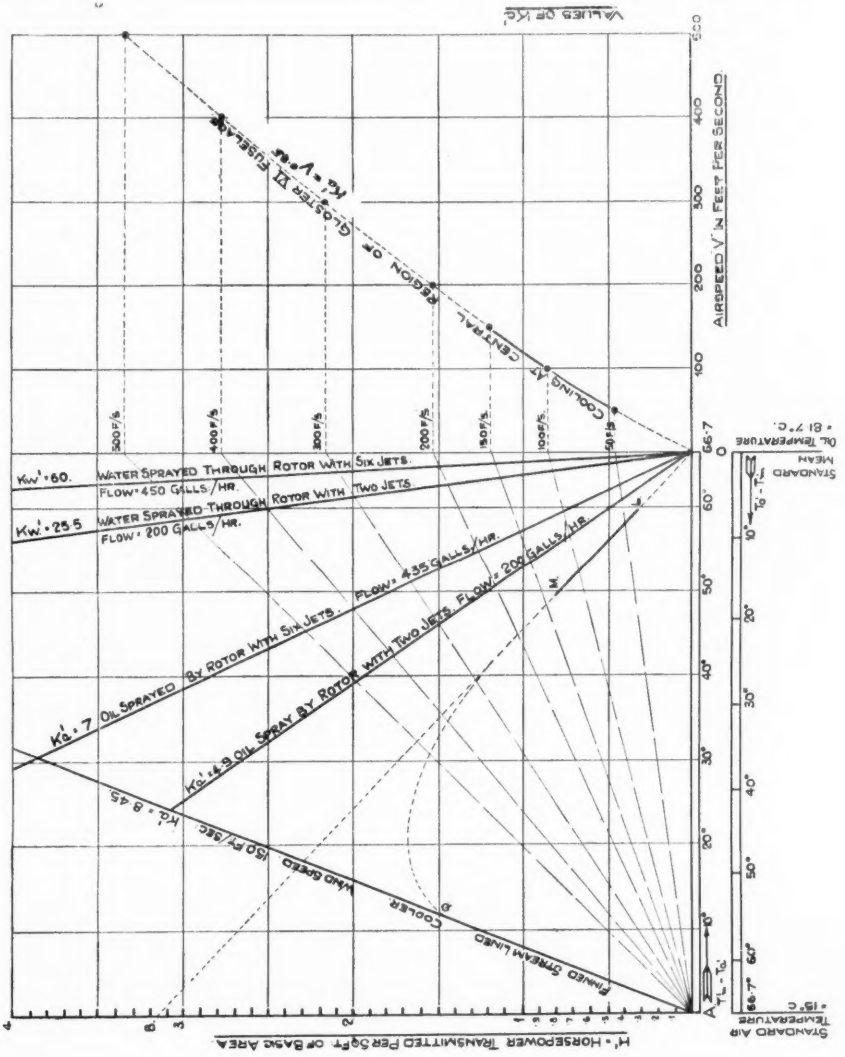
The effect of adding efficient fins projecting into the airstream is to increase the slope of the ACP line for given air conditions, and such fins greatly increase the rate of cooling if the OCQ line is steep in the region concerned; otherwise the fins may be worse than useless.

In Fig. 2 some of the quantitative results are given on a graph prepared for the standard conditions indicated. The line LM represents the results of wind tunnel tests made at the R.A.E. on a flat tube oil cooler as fitted to the Gloster VI seaplane. The tests were full-scale using a dummy fuselage, and the ACP lines for the various airspeeds were deduced on the assumption that the heat transfer coefficient varies as the 0.85 power of the air speed.

The efficiency is very high in the speed range of the wind tunnel tests, but it falls to 50 per cent. or lower at a flying speed of 500 ft. per second. The extrapolation to this speed is probably not correct within close limits, but it suffices to indicate roughly the performance of the cooler at flying speed.

To correlate horsepower dissipated, oil flow, and change of oil temperature, it is useful to remember that for an oil flow of 300 gallons per hour, each degree Centigrade of temperature change represents approximately one horsepower—and pro rata for different flow rates.

As they may be of interest, some results of tests with a spray cooler are given in Fig. 2. The tests were made with a finned cooler as described in the paper, except that there were a few horizontal fins on the lower surface. The



basic area of the cooler was two square feet and the results have been plotted in terms of heat transference per square foot of basic area.

The slope of the metal-air line corresponds to a wind speed of 150 ft./sec. and was deduced from tests made with water circulated through the cooler at high rate, the dissipation from the cooler for standard conditions being about 17 horse-power. Although the oil-metal lines are steep for such, the heat dissipation with oil is less than half the ideal dissipation for the air conditions concerned. This is because the metal-air line is very steep on account of the external fins. The value of H is very high and there is scope for making it still higher with development of the internal finning and adjustment of the jet directions. It is a feature of spray coolers located above the oil in the service tank that, in the event of the cooling element being shot through, the rate of loss of oil is relatively small—giving a correspondingly long range for a forced landing.

It should be remarked that there is considerable evidence from cooler tests that the metal-air heat transference coefficients for cooling elements such as the Vickers-Potts, and elements of lenticular form, are from two to three times those represented by the skin friction of a corresponding flat plate with turbulent boundary layer: that is, as it happens, from two to three times the values given in Fig. 2 for a region of the surface of the Gloster VI fuselage located just behind the pilot's cockpit. Greater drag is of course involved with this greater cooling.

Reply to Discussion

He noted that Wing Commander Cave-Browne-Cave was as enthusiastic as ever about steam cooling. He was amongst the first advocates of its use for aircraft and no doubt would be pleased with the progress now being made with this system of cooling. He had not intended in any way to suggest that evaporative cooling was impracticable, indeed, he was very optimistic about its future. The work at Farnborough had been done to test the practicability of the scheme and refinements in design could come later. It was realised that each type of aircraft would have to be considered separately and a scheme designed to fit the requirements of that aircraft. In spite of the fact that the system used at Farnborough was an adaptation there was a reduction in weight over the standard aircraft and he had no doubt that when a machine was designed to include evaporative cooling the weight would be still further reduced.

As regards the amount of water cooling experienced in the triangular radiator used in the first experiments, this amount, no doubt, could have been reduced by the introduction of a baffle plate or by an independent separator, but it was not considered to be of sufficient importance having regard to the scope of these early tests.

As stated by Wing Commander Cave-Browne-Cave, the elimination of the air from the condensers is important if the cooling surface is to be used efficiently. Apparently the condensers used in these tests satisfied these conditions, as when running up to power the dividing line between the hot condensing surface and cold surface representing the movement of the steam along the condenser was quite distinct. With large wings the same measure of elimination of air may be difficult. An alternative is to use a condenser formed by a double skin construction in which the cross sectional area is such as to preserve a moderate velocity throughout. The steam should drive out the air in front of it with but little admixture and there seems no reason for this form of construction to be any heavier than the other.

Major T. M. Barlow's remarks as to the success his firm have attained with evaporative cooling are interesting, and although the type of condenser used may not be entirely dragless it appears to have the merit of simple and compact installation qualities.

In considering the question of water loss, the cooling surface required on climb is possibly 40 per cent. greater than that for level flight, and it appears quite reasonable to permit a small loss of steam during climb to avoid the provision of an extra and seldom used cooling surface.

Major Green said that apparently the drag of an aircraft at 150 m.p.h. absorbs about 14 per cent. of the h.p. of the engine, this would appear to be approximately so. With a good cooling system a radiator drag at 150 m.p.h. is normally about 9 per cent. or, if interference drag is taken into account, a little over 10 per cent. If the weight of the radiator system be considered the equivalent drag is of the order of 12 per cent. and this may rise to 14 per cent. under tropical conditions.

The suggestion made to use a combined system of cooling on the compression ignition engine whereby the cylinder walls were cooled in the ordinary way and the temperature of the combustion chamber maintained as high as possible by means of steam cooling has greater complication and does not appear to offer any advantage over normal steam cooling.

With regard to the loss of power experienced when using high temperature coolants, this loss can be restored in a simple manner if the engine is a supercharged one, but of course there will be a small drop in the supercharged height of the aircraft. This does not mean that the supercharger is to be increased, but only that the engine throttle would be open a little more than usual at any height.

In reply to Colonel Fell, if an engine developed to run at normal water cooling is then run with a high temperature coolant at say, 150° C., it is more than likely there will be some difficulty experienced due to heat in the cylinder head components, particularly the method of attachment of the head to the cylinder barrels, the valve seats and valves, and possibly pistons and piston clearances. I think that in the U.S.A., where ethylene glycol is being used, these difficulties have already been met. It is true that the power may be depreciated a little, but as already stated, this may be more than compensated for by a reduction in radiator drag.

Mr. Chatterton doubts if evaporative cooling or any alternative system gives any advantage over the present system in motor cars. Reduction in drag at the moment is relatively unimportant except for racing cars, but most present-day cars appear to require a long period of warming up before they will run at all smoothly. This period would be considerably shortened by the use of evaporative cooling as there would be practically no circulation until boiling temperature is reached. Further, the temperature of operation is automatically controlled to that of the boiling point of water, a temperature at which cars as at present designed run very smoothly.

In hot countries ethylene glycol has proved very useful in motor cars which, at the high atmospheric temperatures experienced, are found to be under-radiatored. The water continually boils off and frequent replenishment is necessary. On filling up with ethylene glycol the temperature can then rise above 100° without loss of coolant and the cars are enabled to run in circumstances where otherwise it would have been quite impossible.

In reply to Mr. Manning, the tests using ethylene glycol were not conclusive as to the effect on the thermal efficiency. There was apparently a small drop in efficiency, but as the engine was found to be defective immediately after the tests the data obtained are not reliable.

As regards oil cooling the method of passing the intake air of the engine through the crankcase to cool the oil has been tried on one or two occasions. This scheme appears to be limited to compression ignition engines on account of fire risk with petrol engines and even with the former there is danger, as revealed in the course of the discussion. For petrol engines there is a further difficulty that unless lubricating oil is entirely taken out of the air the highest

useful compression ratio of the engine may be lowered, due to the admixture of the oil.

Referring to Major Green's remarks on oiliness, while it is recognised that fatty oils, and in particular fatty acids, are superior to mineral oil lubricants with respect to " oiliness," the conditions in aircraft engines are such that liquid film lubrication is maintained throughout the engine and, therefore, the friction reducing properties associated with a mineral oil lubricant of appropriate viscosity are sufficiently good to satisfy the requirements of the engine. It is generally considered that an oil of good " oiliness " retains more of this property with increase of temperature than an oil with less of this quality.

In reply to Mr. Duckham, the possibility of corrosion being set up by water and oil emulsions would appear to rule them out from the category of suitable lubricants for aircraft engines. At the temperatures at which they have to function a considerable amount of water vapour would be evolved which would be partly condensed in such parts as reduction gears where corrosion would probably be set up.

Where ethyl fluid is used in the fuel the probability of corrosion would become almost a certainty owing to the evolution of hydrobromic acid which occurs during the combustion of the " dope."

In aircraft engines lubrication is invariably of the dry sump variety, consequently, when the aircraft is not being flown—and such periods of rest are often prolonged—should a breakdown of the emulsion occur in the tank holding the lubricant, since the oil supply is taken from the bottom of the tank, water only would be supplied to the bearings when the engine was first started up.

The possibility of freezing of the emulsion in cold weather must also not be overlooked.

The question of heat transfer of an oil cooler appears to be closely associated with pressure as will be noted in Fig. 8 of the paper. This appears to coincide somewhat with Mr. Duckham's experience, but there is no question that in the usual type of oil cooler there is always difficulty in reducing the cold layer of oil next to the metal surface.

As mentioned by Colonel Fell, cooling the oil through the medium of air flow over the crankcase sump appears to be very reasonable and practical. Already at least half of the oil cooling is done in the piping and the crankcase and if the sump could be blended in to form part of the aircraft cowling much additional oil cooling should be obtained with no increase in drag. He, Captain Swan, had no experience of the Stancliffe cooler.

In reply to Major Bulman, the suggestion to use hotter oils is in a sense analogous to using higher temperature coolants so that they may be cooled more efficiently in respect to the drag imposed. In addition, the troubles inherent in oil cooling would be reduced and there is no difficulty as regards load carrying capacity at the temperatures suggested. The temperature of the oil was given in the paper as 70° C. entering the engine and not leaving it as Major Bulman stated.

Mr. Chatterton's question on the efficiency of oil coolers may best be explained by reference to the chart described and submitted by Major Carter, to whom I am indebted for the diagram. The effect Mr. Chatterton has in mind is represented in the oil chart by moving the H_a line parallel to itself until it intersects the H_o line at the maximum point. There are no definite test results to enable the H_o line of a cooler to be plotted for given conditions, that is constant oil flow or constant pressure drop and the curve of the H_o line is inferred rather then established. If this inference is correct there would seem to be confirmation of Mr. Chatterton's opinion that there is a critical temperature of the air at which the cooling efficiency would be a maximum.

PROCEEDINGS

FIFTH MEETING, FIRST HALF, 66TH SESSION

The Fifth Meeting of the First Half of the 66th Session of the Royal Aeronautical Society was held in the rooms of the Royal Society of Arts, 18, John Street, Adelphi, London, W.C.2., on Thursday, December 4th, 1930, for the reading and discussion of a paper on "The Use of Small Wind Tunnels in Aeroplane Design," by Mr. H. Glauert, M.A., F.R.Ae.S. The President (Mr. C. R. Fairey) was in the Chair.

The PRESIDENT: He supposed there was not a designer of aircraft who had not at some time regretted bitterly having accepted as gospel truth the information provided by the wind tunnel; at the same time, he did not believe there was a designer who had not been obliged to go back to the wind tunnel for information. The older designers, at least, had always regarded it as a rather undependable ally.

Introducing Mr. Glauert, the President recalled that Mr. Glauert had contributed notable papers to the Society on previous occasions, and had never failed to present his subjects in a most informative and interesting manner. He had been a Fellow of the Society since 1918, and had been engaged on aerodynamical research at Farnborough since 1916.

THE USE OF SMALL WIND TUNNELS IN AEROPLANE DESIGN

BY

H. GLAUERT, M.A., F.R.Ae.S.

In January of this year Mr. R. McKinnon Wood read a paper before the Society on the new American wind tunnels, and in his paper he emphasised the importance of making tests at values of the Reynolds number which are actually obtained in flight. These modern developments of wind tunnel design comprise firstly the compressed air tunnel in which high values of the Reynolds number are obtained by testing models of the usual dimensions in a stream of air compressed to 20 atmospheres, and secondly the large wind tunnel with a free jet of 20 to 25 ft. diameter in which it is possible to test the airscrew and fuselage of an aeroplane of moderate size. Mr. Wood also emphasised the importance of a high speed wind tunnel for certain special classes of experiment.

The ambition to achieve the full-scale Reynolds number in our experiments, to make tests on actual aeroplanes under laboratory conditions, and to realise high speeds in other tests, may lead to some disparagement of the older wind tunnels and more particularly of the humble 4 ft. tunnel; and my object in this paper is to bring forward a plea in defence of these poor relations of the modern plutocratic tunnels. I find some support in the fact that Mr. Wood's lecture included a few words in support of the usefulness of these small tunnels, and that this view was supported by some members who took part in the discussion. Before proceeding further, I wish to express my obligation to the Air Ministry for permission to prepare this paper, but at the same time I should explain that the paper expresses only my own personal views on the question. I cannot

claim intimate knowledge either of wind tunnel technique or of the details of aeroplane design, and I fully expect to be attacked on one side by my scientific colleagues and on another side by aeroplane designers, but perhaps I may also hope that a discussion of this question may lead to a clearer conception of the utility and of the limitations of small wind tunnels.

Before proceeding to the main question, which is the value of small wind tunnels as an aid in the design of aeroplanes, I may perhaps point out that small wind tunnels—and I refer in particular to the 4 ft. tunnel—are undoubtedly valuable for calibrating instruments, such as pressure heads and airlogs, and for certain special items of research. When high speeds, approaching the speed of sound, are required, it is necessary to use even smaller tunnels, and here too a small tunnel is of great value. As an aid to design, however, the small tunnel suffers from two important limitations:—

(1) The scale of the test, since the small dimensions of the model imply the impossibility of achieving anything but a small fraction of the full-scale Reynolds number.

(2) The detail of the model, since the small dimensions of the model also make it difficult or even impossible to reproduce correctly the minor details of the form of the aeroplane.

I propose to postpone the discussion of the second limitation to a later stage of the paper, and will remark merely that experience is the only guide to determine which details are important and which are unimportant in the representation of any specific component of an aeroplane. As regards the first limitation, the ideal course is clearly to achieve the true Reynolds number by means of a compressed air tunnel or of a large tunnel, but my aim in this paper is to consider how far we may safely depart from this ideal and accept experimental results obtained at lower values of the Reynolds number. The proposition which I shall try to establish is that, partly by means of our improved theoretical knowledge and practical experience, and partly by means of improved tunnel design, we can obtain from a 4 ft. tunnel experimental results more reliable and more valuable than those obtained ten years ago from our standard 7 ft. tunnels; and I think it would be very rash to assert that those old results had been of no value in assisting aeroplane design.

In my opinion the most important factor which has led to the increased usefulness of our small wind tunnels is our knowledge of the nature and magnitude of the constraint imposed on the flow by the walls of a wind tunnel.[1]* Considering first of all the test of a wing or of a system of wings, we know that the interference of the walls of a wind tunnel with a closed working section is equivalent to a small angle of upwash ϵ_1 in the neighbourhood of the model, and the effect of this upwash is that the angle of incidence and drag coefficient, corresponding to a definite value of the lift coefficient, are both measured too small in the wind tunnel. The magnitude of this angle of upwash in a tunnel with the usual square cross-section[2] is:—

$$\epsilon_1 = 0.274\ \lambda_1 k_L$$

where λ_1 is the ratio of the total wing area of the model to the area of the cross section of the tunnel, and the appropriate corrections to the observed values of the angle of incidence and the drag coefficient are simply

$$\Delta\alpha = \epsilon_1$$
$$\Delta k_D = \epsilon_1 k_L$$

The accuracy of these correction formulæ has been amply verified by special experimental tests, and Fig. 1 shows the excellent agreement between the corrected values of the drag coefficient obtained from tests in a 4 ft. and in a 7 ft. tunnel of a biplane model of span 3 ft. and of area 3 sq. ft. Since the correction

* See list of references at the end of the paper.

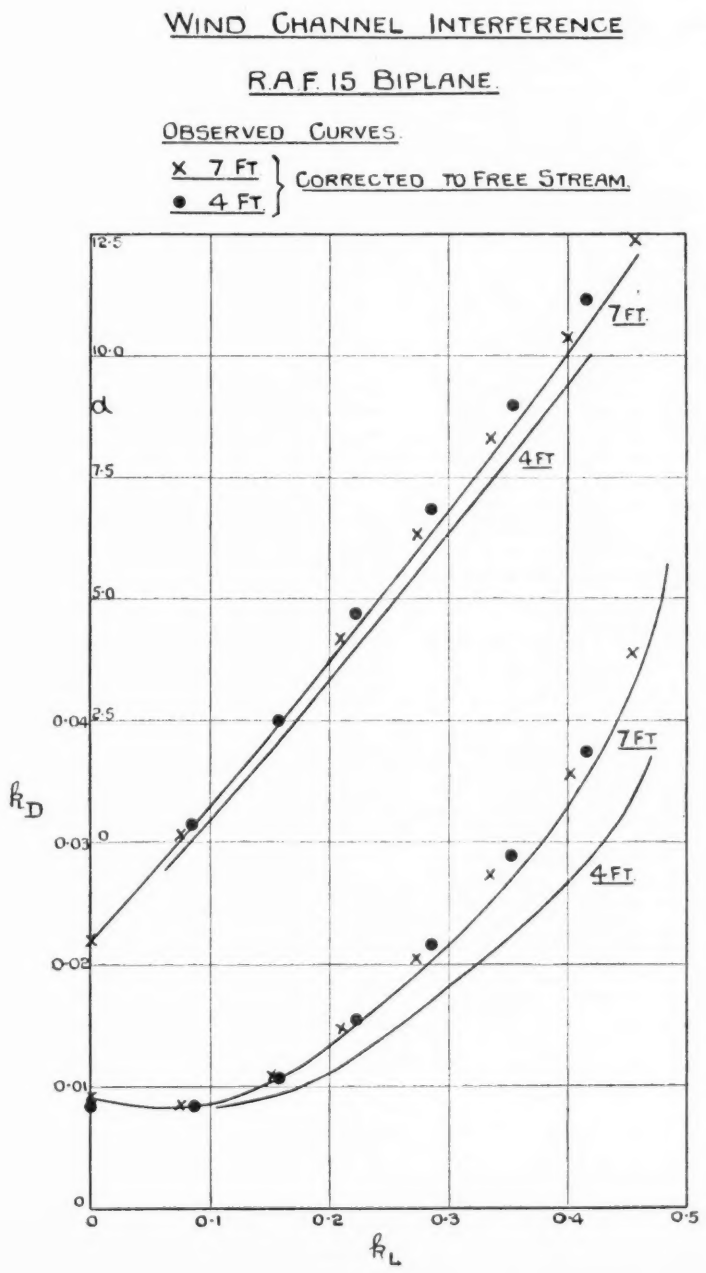

WIND CHANNEL INTERFERENCE
R.A.F. 15 BIPLANE.
OBSERVED CURVES.
× 7 FT
• 4 FT
CORRECTED TO FREE STREAM.
12·5
10·0
α
7·5
5·0
2·5
0
0·04
0·03
0·02
0·01
0
k_D
0
0·1
0·2
0·3
0·4
0·5
k_L
7FT.
4FT.
7FT
4FT

FIG. 1.

is inversely proportional to the area of the cross-section of the tunnel, the correction for a given wing system tested in a 4 ft. tunnel is roughly three times the correction in a 7 ft. tunnel; and even if the assumed value of the correction is in error by as much as one third of itself, the corrected results obtained from a 4 ft. tunnel will still be as accurate as uncorrected results obtained from a 7 ft. tunnel. Actually the uncertainty of the correction formula is quite small when the span of the model does not exceed three quarters of the width of the tunnel, and by virtue of our knowledge of this correction we are justified in testing in a 4 ft. tunnel wing systems whose span is as high as 3 ft. or whose total area is as high as 4 sq. ft.; the results so obtained will be more reliable than uncorrected results obtained from a 7 ft. tunnel. Provided that the same wind speed is obtained in the two tunnels, we can therefore obtain in a 4 ft. tunnel the same value of the Reynolds number which could previously have been obtained with reasonable accuracy in a 7 ft. tunnel.

The theory of this interference correction has been examined in greater detail by Terazawa[3] and Rosenhead,[4] and their more accurate formulæ should be used when the span of the wing exceeds three quarters of the width of the tunnel or if the area of the wing is unduly large. Rosenhead in his analysis assumes elliptic distribution of lift across the span of the wing and Terazawa assumes uniform distribution. If the wing extended from wall to wall of the tunnel the distribution of lift would be uniform across the whole span, and if the span of the wing is only slightly less than the width of the tunnel the distribution probably departs from uniformity only in close proximity to the wing tips. For large spans I think, therefore, that Terazawa's analysis should give a close approximation to the true value of the interference. His formula may be put in the previous form

$$\epsilon_1 = N\lambda_1 k_L$$

but N is now a number depending on the ratio of wing span to tunnel width. Numerical values of N are as follows:—

$2s/b$	=	0.5	0.6	0.7	0.8	0.9
N	=	0.288	0.303	0.325	0.362	0.435

The value of N is greater than the value 0.274, which appears in the approximate formula, but the difference does not become important unless the span of the wing exceeds three quarters of the width of the tunnel or unless the area of the wing exceeds one-fifth of the cross-sectional area of the tunnel. I have recently had occasion to use this formula in analysing the tests of a wing of rather extreme dimensions and have found it to be quite satisfactory as a method of correcting the observed angle of incidence and drag coefficient for the interference of the tunnel walls. An exact solution which took account of the actual distribution of lift across the span of the wing would be very valuable, but no one has yet attempted this rather laborious problem.

The same principle of correction for tunnel interference can also be extended to tests of complete models to determine the pitching moment and tail-setting for equilibrium,[5] and in these tests also the corrected results from a 4 ft. tunnel are more accurate than uncorrected results from a 7 ft. tunnel. In the neighbourhood of the tailplane of the model the angle of upwash ϵ_1 previously considered is increased by a further angle ϵ_2, and for a tunnel of square cross-section

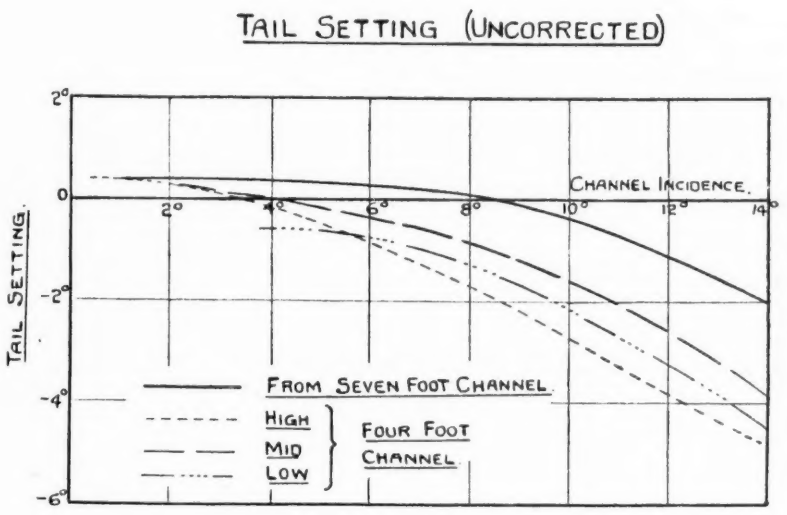
$$\epsilon_2 = 0.480\,\lambda_2 k_L$$

where λ_2 is the value of xS/b^3, b being the height or width of the tunnel, S the total wing area of the model, and x the distance of the tailplane from the centre of gravity. The appropriate corrections to the angles of downwash and tail-setting are respectively

$$\Delta\epsilon = \epsilon_1 + \epsilon_2$$

$$\Delta\eta_T = \epsilon_2$$

The accuracy of these corrections has also been confirmed by special experimental tests, the results of which are shown in Figs. 2 and 3.


TAIL SETTING (UNCORRECTED)
TAIL SETTING.
2°
0
-2°
-4°
-6°
2°
4°
6°
8°
10°
12°
14°
CHANNEL INCIDENCE.
FROM SEVEN FOOT CHANNEL.
HIGH
MID
LOW
FOUR FOOT CHANNEL.

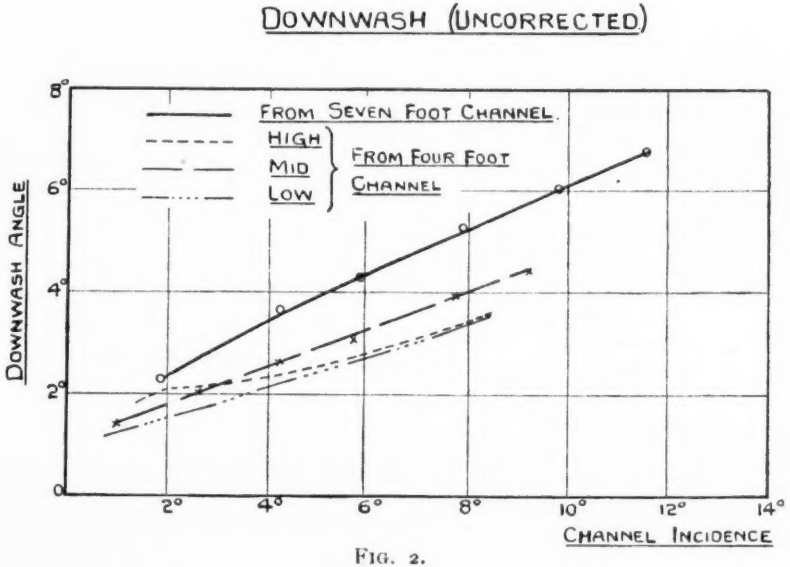
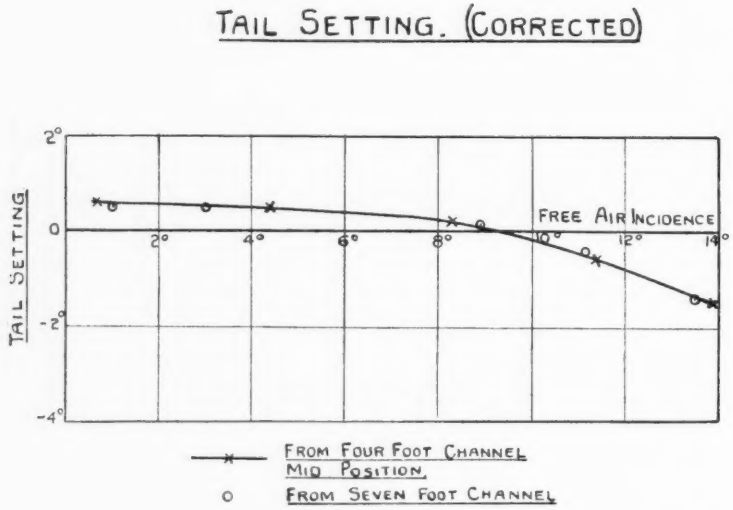

DOWNWASH (UNCORRECTED)
DOWNWASH ANGLE
8°
6°
4°
2°
0
FROM SEVEN FOOT CHANNEL.
HIGH
MID
LOW
FROM FOUR FOOT CHANNEL
2°
4°
6°
8°
10°
12°
14°
CHANNEL INCIDENCE

FIG. 2.


TAIL SETTING. (CORRECTED)
TAIL SETTING
2°
0
-2°
-4°
2°
4°
6°
8°
10°
12°
14°
FREE AIR INCIDENCE
FROM FOUR FOOT CHANNEL MID POSITION.
FROM SEVEN FOOT CHANNEL

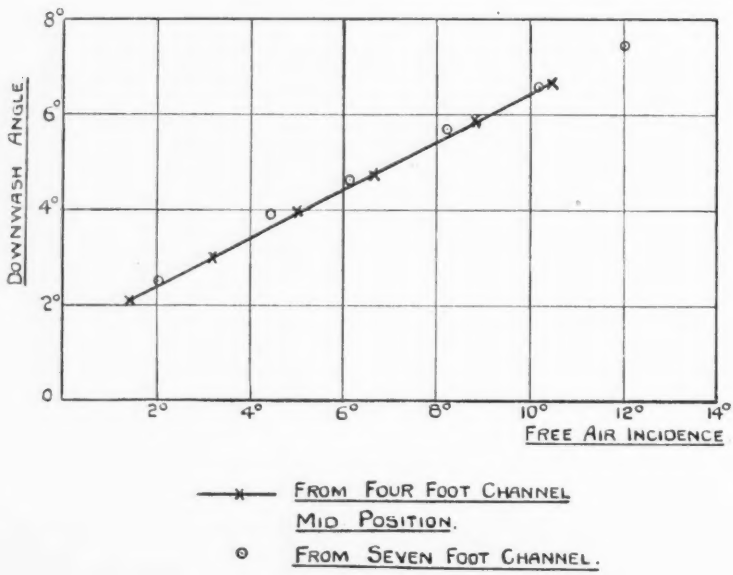

DOWNWASH. (CORRECTED)
DOWNWASH ANGLE
8°
6°
4°
2°
0
2°
4°
6°
8°
10°
12°
14°
FREE AIR INCIDENCE
FROM FOUR FOOT CHANNEL MID POSITION.
FROM SEVEN FOOT CHANNEL.

FIG. 3.

Corrections of a somewhat different type are required for the interference of the tunnel walls on an airscrew[6] tested either alone or in conjunction with a body. These corrections are negligibly small when the model of a complete aeroplane is tested, and become important only when the scale of the model is increased and the airscrew diameter rises to approximately half the width of the tunnel. For such tests of comparatively large airscrews and bodies, however, it is better to use a wind tunnel with an open jet, since the interference in such a tunnel is negligibly small, even when the diameter of the airscrew is large as two-thirds or three-quarters of the diameter of the jet.[7] In this connection I may perhaps mention that the tunnel interference on a body, often referred to as the " choke " correction, was greatly over-estimated some years ago. The argument used was that if the area of the maximum cross-section of the body is S and that of the cross-section of the tunnel is C, then the mean velocity in constricted passage will be $VC/(C-S)$ instead of the tunnel velocity V, and that this increased velocity is the effective velocity experienced by the body. This argument fails, however, owing to the nature of the velocity distribution round the body. In order to illustrate this point I have prepared a diagram (Fig. 4) which shows the velocity in the equatorial plane of a sphere. At the surface the velocity is 50 per cent. greater than the velocity of the stream impinging on the sphere, but this velocity decreases rapidly with increasing radius and is less than 1 per cent. in excess at a distance of 4 radii from the centre of the sphere. If we imagine a tunnel wall to be drawn as in the figure, it is only the excess velocity outside this wall which leads to an increased effective velocity, and on this basis the effective velocity is only 1.038 V instead of 1.125 V, as estimated from the primitive " choke " theory. The dimensions shown in the figure form a very extreme example in which the diameter of the body is one-third of that of the tunnel. For more reasonable dimensions the results are as follows:—

d/D	Choke velocity.	Effective velocity.
0.1	1.010	1.001
0.2	1.042	1.008

Even when the diameter of the body is as high as one-fifth of that of the tunnel, the effective velocity is increased by less than one per cent., and since this increased velocity reacts only on some part of the body it is evident that the tunnel interference on the drag of the body must be extremely small.

The important interference corrections depend essentially on the system of induced velocities associated with the lift of a wing or with the thrust of an airscrew, and they are valid only in the range of moderate angles of incidence below the critical angle. The stalling of a wing is due to a breakdown of the flow over its upper surface, and for our knowledge of the state we have to rely wholly on experimental tests. Clearly the constraint of the tunnel walls may modify the conditions which govern the stalling of a wing, and hence there may be a tunnel interference on the maximum lift coefficient of a wing. Some experiments have recently been made at the Royal Aircraft Establishment to investigate this interference, and the results of these experiments are shown in Fig. 5. The aerofoils tested comprised two with a low maximum lift coefficient (aerofoil A and R.A.F. 30), one with a fairly high maximum lift coefficient (R.A.F. 32), and one with a very high maximum lift coefficient (R.A.F. 19). The experiments were made in tunnels of square and of rectangular cross-section, and rather to our surprise they showed that the increase in maximum lift coefficient due to the constraint of the tunnel walls was independent both of the shape of the aerofoil and of the height of the tunnel. The correction appears to be proportional to the ratio of the area of the aerofoil and inversely proportional to the square of the width of the tunnel, and its magnitude is represented by the formula

$$\Delta k_L \text{ (max.)} = -0.38\, S/b^2$$

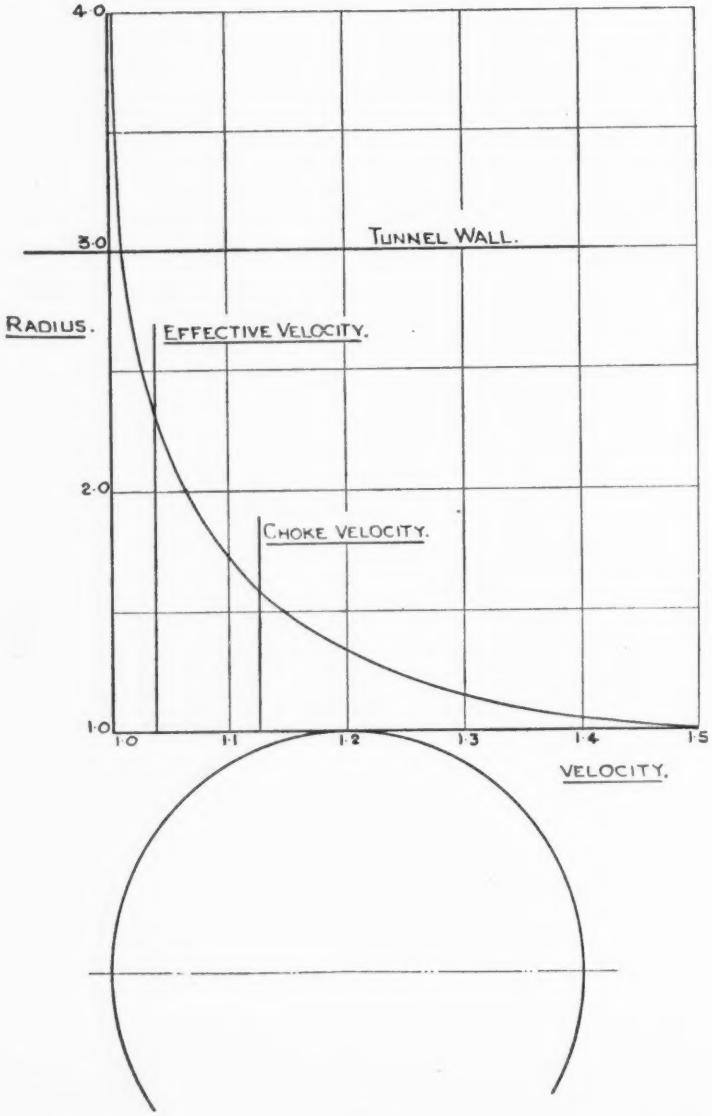

FLOW PAST A SPHERE.
4·0
3·0
2·0
1·0
RADIUS.
TUNNEL WALL.
EFFECTIVE VELOCITY.
CHOKE VELOCITY.
1·0
1·1
1·2
1·3
1·4
1·5
VELOCITY.

FIG. 4.

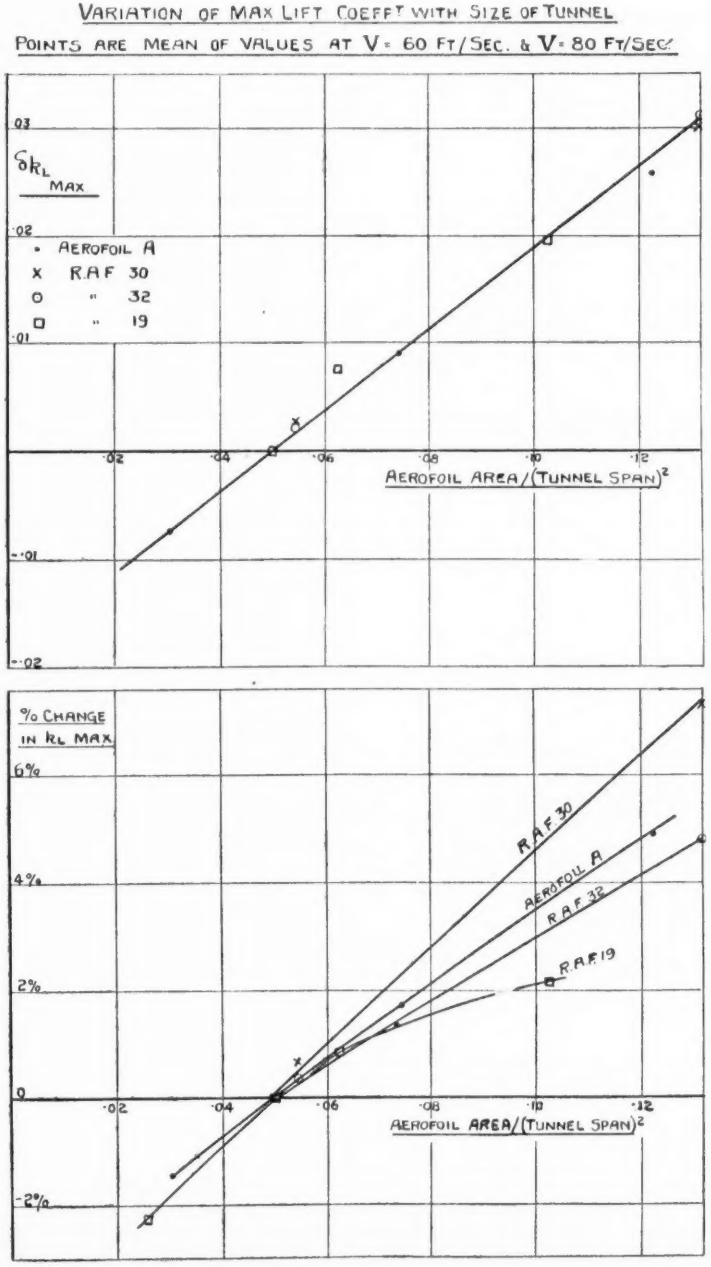

VARIATION OF MAX LIFT COEFFT WITH SIZE OF TUNNEL
POINTS ARE MEAN OF VALUES AT V = 60 FT/SEC. & V = 80 FT/SEC.
σk_L MAX
·03
·02
·01
-·01
-·02
• AEROFOIL A
X R.A.F 30
O " 32
□ " 19
·02
·04
·06
·08
·10
·12
AEROFOIL AREA/(TUNNEL SPAN)²
% CHANGE IN k_L MAX
6%
4%
2%
0
-2%
R.A.F 30
AEROFOIL A
R.A.F 32
R.A.F 19
·02
·04
·06
·08
·10
·12
AEROFOIL AREA/(TUNNEL SPAN)²

FIG. 5.

Thus, for example, the maximum lift of a wing of area 1.5 sq. ft. is 0.035 higher in a 4 ft. tunnel than it would be in free air. From the form of the correction we may perhaps deduce that the nature of the interference is a stabilising of the flow by the lateral walls of the tunnel, similar perhaps to the effect which would be produced by end plates on the wing tips.

Although the knowledge of these interference corrections enables us to test in a 4 ft. tunnel models of a size which would previously have required a 7 ft. tunnel for accurate experiments, there remains the difficulty that these tests will of necessity be made at a low value of the Reynolds number. Assuming a wing chord of 6 in. and a wind speed of 80 ft./sec., the Reynolds number of the test is approximately 250,000, whereas the Reynolds number attained in flight by aeroplanes of moderate dimensions ranges from two to five millions at low speed, and may rise to 10 or 15 millions at high speed. We cannot hope to attain these high values in an atmospheric wind tunnel of moderate dimensions, but we can at least reduce the gap a little by improving the design of our wind tunnels. The power ratio of a wind tunnel is defined as the ratio of the power used to the kinetic energy of the air passing through the working section every second. The power ratio of the N.P.L. type of wind tunnel is approximately 2.0, but this value can be reduced very considerably by an improved design of tunnel. Thus the power ratio of the new 5 ft. open jet tunnel at the Royal Aircraft Establishment is roughly 0.4, and I understand that a value as low as 0.2 has been obtained in a new American tunnel. If we accept 0.4 as a reasonable value for a modern wind tunnel, it is possible to reduce the power consumption to one-fifth of its old value, or alternatively to increase the wind speed by 70 per cent. The wind speed in our typical 4 ft. tunnel will then rise from 80 to 135 ft./sec. and the Reynolds number of our tests will rise from 250,000 to 425,000. This is only a small step to bridge the gap from model to full-scale values of the Reynolds number, but it is an important step.

It is perhaps a little misleading to think in terms of the Reynolds number, since we know by experience that, with a very few exceptions, the most important variations of lift and drag with increasing scale of test occur at low values of the Reynolds number. A change of 100,000 in the Reynolds number may be important in our model tests, but will be quite negligible in flight. A more suitable method is to use the logarithm of the Reynolds number as criterion, and then an increase of 0.3 in this value corresponds to doubling the Reynolds number at any part of the range; but even in this representation the lower part of the scale is the most important. In Fig. 6 I have prepared a diagram, which may perhaps be called the logarithmic ladder of Reynolds number. Each successive rung of this ladder represents a doubling of the Reynolds number, whose logarithm is given on the left hand side. Against each rung I have written the details of a model or full-scale condition which will represent this Reynolds number, and it will be seen that each rung of the ladder is now occupied. The old 4 ft. and 7 ft. tunnels, without correction for interference, would occupy the two bottom rungs of the ladder and there were then two empty rungs before we reached the condition of a small aeroplane at its lowest speed. Now, by our knowledge of the interference corrections, and by improvement of our tunnel design, the whole ladder is full and the highest value obtained in a 7 ft. tunnel nearly reaches the lowest value obtained in flight.

We must now consider how high it is necessary to climb up this ladder before we can predict reliably what will occur at the top of the ladder. The two characteristics of a wing which need special consideration are the minimum drag coefficient at a small angle of incidence and the maximum lift coefficient at the critical angle, but in the intermediate range the scale effect on the lift coefficient is known to be very small, and any scale effect on the profile drag coefficient is only a small fraction of the induced drag coefficient which is not susceptible to scale effect. There is, unfortunately, no hope of determining

SCALE OF REYNOLDS NUMBER.

		Chord.	Speed.
7.2 ————	Racing Aeroplane, top speed ...	5ft.	340 m.p.h.
6.9 ————	Fast Aeroplane, top speed	5½ft.	160 m.p.h.
6.6 ————	Large Aeroplane, landing	8ft.	55 m.p.h.
6.3 — — —	Small Aeroplane, landing	5ft.	45 m.p.h.
6.0 ——— —	Modern 7ft. tunnel	15in.	130 f.p.s.
5.7 ————	Modern 4ft. tunnel	7½in.	130 f.p.s.
5.4 ————	Corrected 4ft. tunnel...	6in.	80 f.p.s.
5.1 ————	Uncorrected 4ft. tunnel	3in.	80 f.p.s.

FIG. 6.

reliably the maximum lift coefficient of a wing by tests in a 4 ft. wind tunnel. By means of the developments already discussed it is possible to raise the Reynolds number of the test from 125,000 to 500,000 and to correct the observed values for the interference of the tunnel walls, but nevertheless there often remains an important discrepancy between the model and full-scale values of the maximum lift coefficient. We know by experience that the scale effect on thin wings of low camber, such as R.A.F. 15, is small and that the maximum lift coefficient of thick wings tends to increase with the Reynolds number, but occasionally the value begins to fall again at a still higher Reynolds number in the full-scale range, and we can never be sure that a wing will not develop some peculiar behaviour of its own. For the value of the maximum lift coefficient we must therefore rely on determinations made in flight or on experiments in a wind tunnel which can realise the actual Reynolds number. This implies, of course, the use of a compressed air tunnel, or of a large wind tunnel capable of testing half-scale models at double the stalling speed. I do not think it is possible or safe to make any generalisation from the values which have already been obtained by these means, but I myself use as a rough working rule that the scale effect on the maximum lift coefficient of wings of conventional shape is small if the thickness-chord ratio is equal to twice the camber of the centre line, *i.e.*, if the maximum thickness is equal to twice the mean ordinate at the centre of the wing, and that the maximum lift coefficient increases with scale if the thickness is greater than this value.

The position as regards the minimum drag coefficient of a wing is not quite so discouraging since we have obtained already a better knowledge of the variation of friction drag with Reynolds number, and since anomalous behaviour of a wing is less frequent. In Fig. 7 I have drawn the two curves of the drag coefficient of a flat plate with laminar and with turbulent flow in the boundary layer, and also a transition curve which is calculated on the assumption that laminar flow persists over the front part of the plate as far as the point corresponding to a Reynolds number of 500,000. Our model tests are made usually in the region where the laminar curve is passing to the transition curve, and on first thoughts it might appear to be a hopeless task to predict from these tests

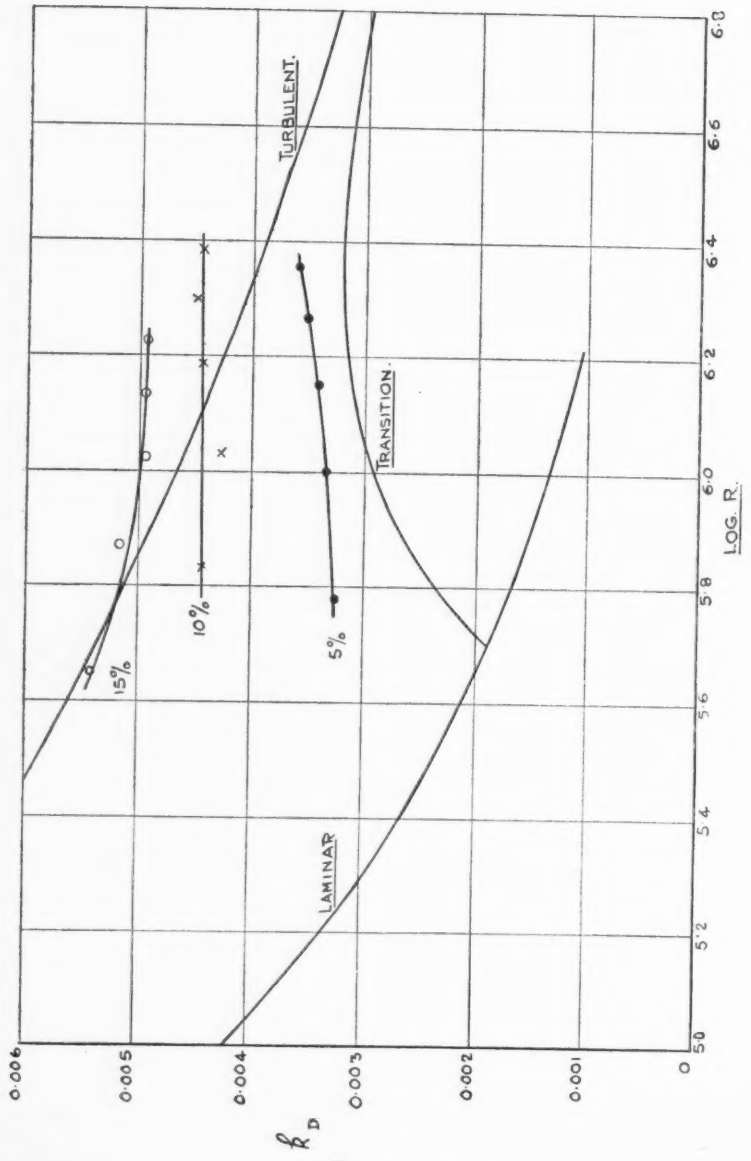

SCALE EFFECT ON DRAG.
TURBULENT.
TRANSITION.
LAMINAR
15%
10%
5%
LOG. R.
C_D
0·006
0·005
0·004
0·003
0·002
0·001
0
5·0
5·2
5·4
5·6
5·8
6·0
6·2
6·4
6·6
6·8

FIG. 7.

the value to be expected at full-scale values of the Reynolds number. This is indeed the case with streamline forms such as airship hulls whose drag depends almost wholly on skin friction, but I do not think we need be so pessimistic about wing sections. The minimum drag of a wing is due partly to frictional forces and partly to the pressure distribution over the surface, and we have no justification for assuming that the skin friction is identical with that of a flat plate. The pressure gradient along the upper surface of a wing, and more particularly the rise of pressure which occurs immediately after the point of minimum pressure far forward on the chord, reacts on the boundary layer, and causes the flow to become turbulent at an earlier stage than on a flat plate. Thus the transition curve occurs earlier and our tests are made at a stage where this transition curve is already merging into the turbulent curve. Also the reduction of frictional drag which occurs as we pass along the turbulent curve is offset by an increase of the form drag due to the development of a more intense turbulent wake. In Fig. 7 I have added three curves of the observed drag of symmetrical sections tested at a high model scale, and these curves do not show any close resemblance to the curves for a flat plate. The scale effect is small, the drag increases slowly for the thin section and decreases for the thick section, and we shall not err greatly by accepting the value obtained at a Reynolds number of 1,000,000. Of course, for complete accuracy we must again rely on tests in a compressed air tunnel or in a large tunnel, but the position is more hopeful than for the maximum lift coefficient because the scale effect is smaller, because anomalous behaviour is less frequent, and because it is possible to arrange the tests to achieve a higher Reynolds number than can be attained in tests of the maximum lift coefficient.

Hitherto I have considered tests of the model of an aeroplane or of its wing system, but if we are interested mainly in the minimum drag coefficient there are some experimental tricks which enable us to increase the scale of the test. We may, for example, test a wing of very low aspect ratio at low values of the lift coefficient, since the induced drag and the tunnel interference are small and any errors of calculation are relatively unimportant. Alternatively we may test a wing stretching almost from wall to wall of the tunnel with small end pieces attached to the walls themselves, and thus obtain directly the characteristics corresponding to infinite aspect ratio. By either of these devices and without proceeding to absurd conditions we can increase the chord to 2 ft. and thus obtain in our 4 ft. tunnel a Reynolds number of the order of 1,500,000. In fact, by using a modern design of 4 ft. wind tunnel which gives a wind speed of 130 f.p.s. and by adopting the most suitable method of experiment, we can conduct experiments to determine the maximum lift and minimum drag of a wing at approximately one-quarter of the Reynolds number which is attained by an aeroplane of moderate size and moderate speed.

Special experimental devices are also of value if we are interested in the design of the airscrew and body, or in their mutual interference. Since the interaction of the body and wings will be due mainly to the central parts of the wings, it is legitimate to make the model on a larger scale, but with the end portions of the wings omitted so that the model will fit into a 4 ft. tunnel. Alternatively, if the tunnel is of the open jet type, we may make a complete model and allow the ends of the wings to project beyond the boundary of the jet. Owing to the uncertainty associated with the wing tips, neither of these experiments give an absolute determination of the lift or drag of the aeroplane, but they do give reliable estimates of the effect of changes in the body or airscrew. They may be used to compare different airscrews, to determine the gain due to cowling the engine, or to determine the best position of the body relative to the wings. An experimental check on the validity of this type of experiment has been obtained recently by some tests in the new 5 ft. open jet tunnel at the Royal Aircraft Establishment. Using a 1/5th scale of the Bristol

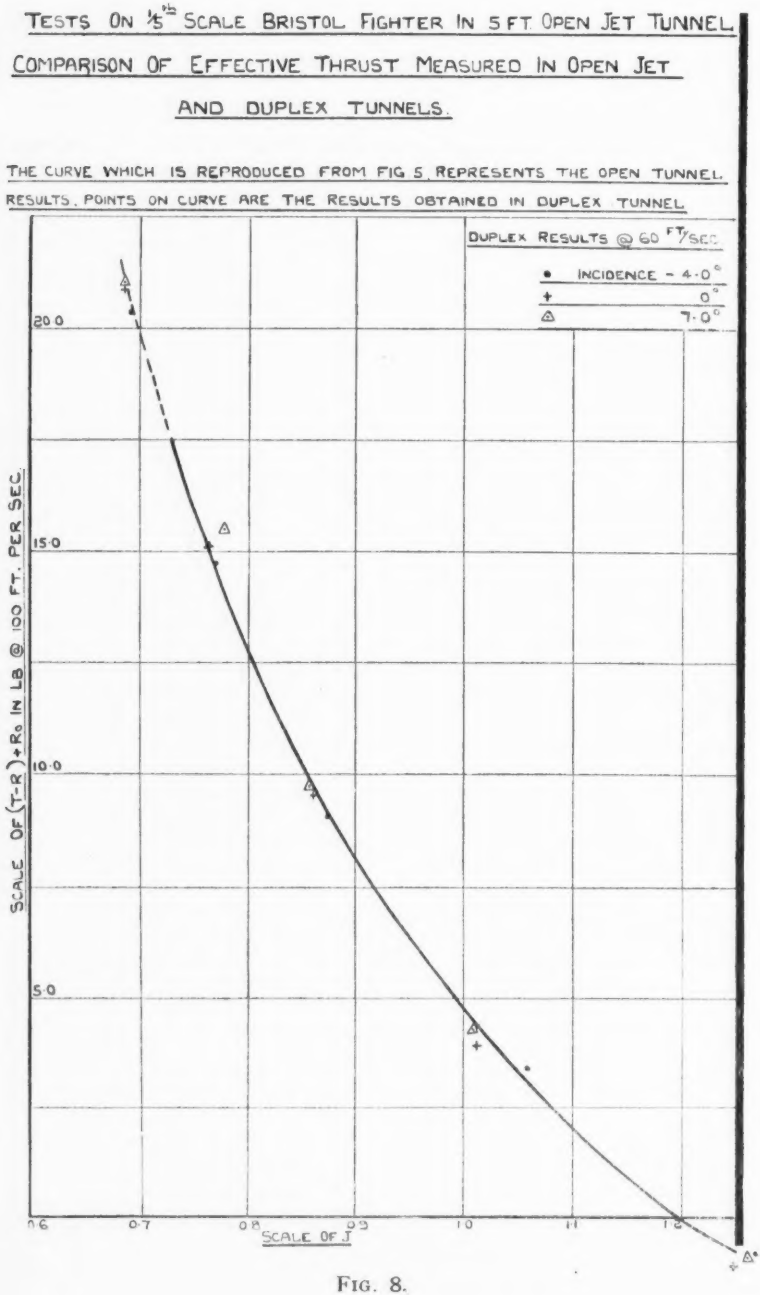

TESTS ON 1/5TH SCALE BRISTOL FIGHTER IN 5 FT. OPEN JET TUNNEL.
COMPARISON OF EFFECTIVE THRUST MEASURED IN OPEN JET AND DUPLEX TUNNELS.
THE CURVE WHICH IS REPRODUCED FROM FIG 5 REPRESENTS THE OPEN TUNNEL RESULTS. POINTS ON CURVE ARE THE RESULTS OBTAINED IN DUPLEX TUNNEL.
DUPLEX RESULTS @ 60 FT/SEC.
INCIDENCE - 4·0°
0°
7·0°
SCALE OF (T-R)÷R₀ IN LB @ 100 FT. PER SEC.
20·0
15·0
10·0
5·0
0·6
0·7
0·8
0·9
1·0
1·1
1·2
SCALE OF J

FIG. 8.

Fighter aeroplane with its wings projecting beyond the boundary of the jet, the experiment consisted of testing the model without airscrew and with airscrew running. The first experiment determines a drag D_0 and the second experiment determines the excess of thrust over drag $(T-D)$. The effective thrust of the airscrew is therefore $(T-D+D_0)$, and Fig. 8 shows that the effective thrust so determined was identical with the value obtained by tests of the complete model in the duplex tunnel at the National Physical Laboratory.

Similar experimental devices can suitably be used for tests of engine nacelles situated on the wings or for end fittings where a strut runs into a wing. In my opinion the most hopeful method of experiment is to use a wing stretching across the tunnel and simulating the condition of infinite aspect ratio. If then the increase of drag due to adding a nacelle or the change of drag due to modifying its shape be determined as a function of the lift coefficient, the drag may be taken to be that which will arise on the complete aeroplane when the local lift coefficient of the wing, at the point where the nacelle is fitted, is equal to the lift coefficient obtained in the wind tunnel test.

By means of these special devices it is possible to increase very considerably the scale of the test, and in general I think it is legitimate to say that by appropriate tests in a modern 4 ft. tunnel we can attain roughly one-fifth of the Reynolds number which will occur in flight with an aeroplane of moderate size. There remains, however, another difficulty which I mentioned earlier in the paper, namely, the difficulty of representing accurately the minor details of the structure. When the size of the model has risen to one-fifth of the full scale, this difficulty is not perhaps too great, but is nevertheless impossible to represent all the details of an engine, or a radiator, or of the mechanism of a slotted wing, and for such tests it is necessary to await the construction of a large wind tunnel.

In spite of these and other limitations, I consider that a 4 ft. wind tunnel, particularly if it be one of modern design, should still prove to be a very valuable aid in the design of an aeroplane, and in conclusion I may perhaps describe what I consider to be the functions of our different wind tunnels in this respect. The 4 ft. wind tunnel should be used for preliminary tests in the early stages of design to determine the best relative position of wings and body, to determine the balance of the aeroplane and the power of the controls, and to investigate the possibility of improvements in minor details. When the main outlines of the design are fixed, experiments with a larger scale model suitable for a larger tunnel may be desirable to clear up any points of uncertainty, and, unless the information is already available, special tests in a compressed air tunnel will be required to determine the maximum lift of the aeroplane. Finally, when the aeroplane has been made, some tests in a large wind tunnel may be desirable to investigate the operation of wing slots and radiators, to improve the radiator system and engine cowling, or to investigate special problems such as shielding of the cockpit. Thus each type of wind tunnel has its special function to perform in achieving the best design of aeroplane, and in this scheme the function of the 4 ft. wind tunnel is to be a constant aid to the designer, ready at hand to answer any question which lies within its province.

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Discussion

The President: He had seldom or never heard a subject of this nature presented in so complete and interesting a manner as Mr. Glauert had presented it. Those designers present who possessed 4 ft. tunnels would leave the meeting with very much increased faith in the possibilities of those tunnels, and those who did not possess tunnels, perhaps because of their ultra distrust of the results obtained therein, might reconsider the matter. The President asked Mr. Glauert's opinion—bearing in mind the high cost of running a tunnel—as to what was the minimum size and type of general purpose tunnel that the ordinary designer or constructing firm could expect to use to-day with sufficient accuracy to be of real service to them.

Mr. R. K. Pierson (Chief Designer, Messrs. Vickers Aviation, Ltd.): He had used a 4 ft. tunnel for a considerable number of years, with very fair success, but the great difficulty which he and his colleagues had experienced in connection with that size of tunnel was to produce the models accurately enough. Of the complete aircraft, for instance, only 90 per cent. could be tested in the tunnel, and the figures for the remaining 10 per cent. must be estimated; that 10 per cent. was a very large proportion. Prandtl corrections for tunnel wall constraint were used for all sizes of model, and no appreciable error had resulted. Corrections for scale effect were made fairly successfully, except in respect of maximum lift. Struts were very difficult to manufacture for a small model; his practice was to represent the struts on the model by means of R.A.F. wires, which produced about five or six times the drag of actual struts, and that needed to be corrected. He was surprised that Mr. Glauert should have thought that the highest Reynolds number should be taken on a complete aircraft in the wind tunnel, and that it could not be evaluated by tests at various wind speeds. He had found that method worked reasonably well, except in the case of high lift coefficients, of course.

Mr. J. D. North (Chief Designer, Messrs. Boulton & Paul, Ltd.): He thanked Mr. Glauert not only for his paper, but also for his valuable missionary work in connection with the vortex theory, and for having done so much to increase the usefulness of the 4 ft. tunnel. At the same time, Mr. North confessed that he was not quite so confident as Mr. Glauert as to the reliability of the interpretations of wind tunnel results in every respect. He held that more accurate wind tunnel work was required in connection with design than was necessary in connection with research—not in the sense of more accuracy of measurement, but a more correct interpretation of what it was one wanted to get at. That statement might be regarded by Mr. Glauert as being heresy, but the point was that anyone engaged in research was given a fair amount of latitude in order to simplify the experimental work, and the conclusions drawn therefrom were merely subject to discussion, whereas in designing an aeroplane one was tied down to obtaining wind tunnel results which were representative of the actual aeroplane, and if those results were inaccurate the fact became painfully evident when the actual aeroplane was tested. Some of the minor inaccuracies were inevitably covered up, because of the great difficulty of obtaining accurate full-scale results. With regard to the measurement of profile drag and maximum lift coefficient, he still believed it was almost true to say that those were the only two things about an aerofoil that one could not calculate, and, as one could not measure them in a small wind channel with any degree of accuracy, he did not think the small atmosphere channel was very helpful in the matter of aerofoil design. It was extremely helpful, however, in enabling one to find out the effect upon the performance of the wing of various obstructions, such as engine nacelles, and so on. Although, as Mr. Glauert had suggested, it might be possible to calculate the local k_L when using low aspect ratio wings in the channel, it did not enable

one to represent the effect of interference on induced drag, which was often the most serious. Not only did it come from bodies, but the effect of the slip stream on the wing was one of induced drag, and it was very difficult to measure that on a reasonable scale in a small channel.

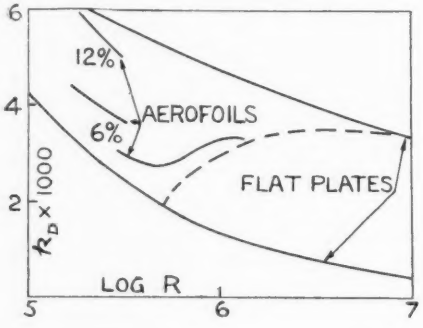
With regard to the transition between turbulence and laminar flow, he said that if one were considering the effect of starting with a streamlined form and gradually turning it into a practical aeroplane body, one must be extremely careful to ensure that one started with turbulent flow to begin with. Some misleading deductions had been made from tests on airship models, as Mr. Glauert had pointed out, and he asked for Mr. Glauert's opinion with regard to experimental methods of ensuring turbulent flow with streamlined models. Experiments had been made by using small rings around the nose and grids in the channel, and results appeared to be reasonably satisfactory. He believed that in the case of the R.101 model, which showed a very low drag coefficient, by the production of artificial turbulence this was put on its proper point on the turbulence curve for the appropriate *VL*.

Finally, he asked Mr. Glauert by what means the Americans had succeeded in reducing the power ratio below the very excellent figure quoted for the new R.A.E. channel.

Major GREEN (Messrs. Armstrong-Siddeley): Although for a good many years his Company had resisted the temptation to instal a wind tunnel, because they did not know how to interpret the results, they had installed one not very long ago, and the results obtained from it were such as to encourage them to continue its use. Inasmuch as Mr. Glauert had given in his paper some further hints as to how the working of wind tunnels could be improved, he believed still greater value would be obtained from their use. Major Green also asked how the Americans had achieved the remarkably fine power ratio which had been mentioned, because, if this Company knew how it was achieved, it might be worth their while to do away with their existing tunnel and to instal a new one.

Dr. PIERCY (Lecturer, East London College): The lecturer had dealt very ably with a question of outstanding and immediate interest to many, viz., the utility of the 4 ft. channel, which modern research seemed at first sight to have placed in a desperate plight. Probably no more daring use had ever been made of aerofoil theory. But with judicious restrictions and with the aid of some recent calculations, they saw, in the result, the small channel receive a new lease of life. Experiment even on so small a scale could evidently, in some cases, reach a long way towards full-scale Reynolds numbers. Nevertheless, the speaker could not quite follow Mr. Glauert's reasons for suggesting that in testing aerofoils they were sufficiently near the merge of the transition curve with the turbulence cure to justify optimism in predicting full-scale minimum drag. Professor Jones had been careful to point out that he did not expect two-dimensional bodies to fall in with flat plate theory as snugly as three-dimensional bodies, but he had included in his papers certain data from wings which required to be taken into account from the engineering point of view. The data was familiar but might perhaps be looked at again. Mr. Glauert's remark as to compensation occurring between skin friction and form drag was interesting and suggestive, yet it was seen that flat plate theory still found some sort of reflection in aerofoils. Of course, the sketch ignored other aerofoils of larger drag, whose variation with scale did not help the argument, but they were concerned primarily with exceptionally good shapes. Turning to Fig. 7 of the lecture, both the thinner shapes appeared to be low-drag aerofoils, and the test figures, on their face value, seemed scarcely to establish the lecturer's view. The 5 per cent. camber curve seemed in course of being pushed up by transition friction, and might be expected to fall considerably again before the largest full-scale

Reynolds numbers were reached. Referring to the aerofoil of 10 per cent. camber, Dr. Piercy said that if Mr. Glauert would permit him to draw a curve through the actual readings shown, the modified curve in this case also would bear a similar interpretation. He asked if Mr. Glauert had other reasons, not immediately apparent, for arriving at a different conclusion.



The question, as was well known, had a two-fold practical significance. There was the difficulty of designing from the model tests, while in addition, with aerofoils subservient to the considerations applying to flat plates, model tests might be different in different channels, so that full-scale allowances became dependent on the channel used, including, of course, the building in which it was housed. The second difficulty was essential because good channels were sometimes of necessity installed in somewhat unfavourable rooms. Certain features of the present East London College Laboratory, for instance, produced "eddy viscosity" in the 4 ft. channel stream, and for a dozen years it had been the practice there, in important cases, to compare model tests carried out in the 4 ft. and in a 2 ft. channel. Looking back, it could be said that the scale effect curves of most aerofoils agreed under this examination, but a few—and among these some interesting ones—differed. It seemed to Dr. Piercy quite clear that a certain number of good aerofoils could not be regarded as having fixed characteristics realisable in all channels. Flat plate theory could not be accepted as a complete or sufficient explanation, but it did appear to offer some present guide.

Many at the lecture were greatly indebted to the N.P.L. for creating the 4 ft. channel. Nearly a score of years had passed, and they looked again to the Air Ministry and the two great Government laboratories for further guidance, whether in the form of the channel or in the technique of its use. Dr. Piercy shared the eagerness of Mr. North and Major Green for details as to how the Americans had achieved the improvement in form to which reference had been made, because great improvements in efficiency might perhaps bring even some very modified compressed air channel within common aspiration.

Dr. G. Douglas (Senior Scientific Officer, R.A.E.): When he had visited some of the Continental wind tunnels a year or two ago he had been impressed by the much higher speeds and the correspondingly crude measuring apparatus used there, as compared with the practice in this country. The apparatus used in this country was influenced very largely by the original balances designed at the National Physical Laboratory, which were very suitable for the accurate measurement of small forces but were rather expensive. If high speeds were adopted, very much simplified balances could be used, and he suggested that it would pay to devote a little more money to the motors and less to the balances.

With regard to the choke correction, he said that Mr. Glauert's method of dealing with it gave a remarkably clear picture of how that correction was made, but it would be interesting to know how generally the numerical values given could be used. He had checked it roughly against Professor Lamb's formula, for a 5/1 body, and had found that, with Professor Lamb's formula, the velocity along the surface was considerably higher than the choke correction suggested. The variation of the maximum lift curves with size of tunnel had fascinated him. He doubted if, in the present state of their knowledge, it was reasonable to apply that correction, and he would like to know to what extent the agreement shown was fortuitous.

Mr. L. W. Bryant: Those who used wind tunnels were especially indebted to Mr. Glauert for his introduction of Prandtl's work into this country, and for his subsequent wide extension of it; he had certainly done a great deal to increase the utility and reliability of the small wind tunnel. Mr. Bryant said that he personally had a liking for the 4 ft. tunnels, having used them much more than he had used the large tunnels. In his experience, the 4 ft. tunnels had always proved equal to the tasks set them, provided, of course, that one realised their limitations. So far from the advent of the larger tunnels being likely to render the small ones obsolete, the small tunnels were proving to be extremely useful for carrying on supplementary researches of a fundamental nature, and by their use we were increasing our general knowledge of aerodynamics. There were numerous special jobs suitable for the 4 ft. tunnel, many of them being of the kind which a designer would wish to have carried out in order to help him to solve some of the problems which he must be meeting continually. Even such questions as the effect of turbulence on drag and the effect of stalling upon stability and control would probably not be permanently outside the province of the 4 ft. tunnel, and he was not sure that they were very far outside at the moment. Mr. Bryant mentioned some experiments he had made with an aerofoil in order to measure heat dissipation. He had a large bundle of electric leads at each end of the span and near the walls of the tunnel. The ratio of the area of obstruction to that of the cross-section of the tunnel was 1 :14, representing a total increased choke velocity of less than 8 per cent.; pressure plotting on the aerofoil, however, showed a velocity increase of as much as $5\frac{1}{2}$ per cent. That rather suggested that near the wall of the tunnel an obstruction has a much larger effect on velocity than an equivalent obstruction in the centre of the tunnel. Mr. Glauert, he concluded, had not mentioned the correction for static pressure drop down the tunnel, which was very important when measuring the drag of long bodies in the existing small closed tunnels. But Mr. Glauert himself had recently produced a rational formula for this correction.

Mr. McKinnon Wood (Principal Scientific Officer, R.A.E.): He suggested that the type of tunnel which might best be adopted by an aircraft constructing firm was the new type that had been installed at Farnborough, and which was referred to in Mr. Glauert's paper. It was, essentially, the Göttingen type of tunnel, but made more compact. The Farnborough tunnel had a diameter of 5 ft. across the jet; the overall dimensions were: Length (including motor) 50 ft., width 20 ft. and height 10 ft., so that the whole space occupied was small. That might be an important consideration. In the near future a paper would be issued giving full particulars of the tunnel and of the experiments carried out on it. The R.A.E. would welcome representatives of aircraft firms who would care to inspect it. He was not certain whether it would be better to have an open jet tunnel or a walled tunnel. The great advantage of a walled tunnel was that one could get a given speed for about half the expenditure of power required with an open jet, the two tunnels being otherwise of the new R.A.E. form. (This is the explanation of the remarkable performance of

the Californian wind tunnel). Moreover, when there was a wall around the stream one knew where the stream ended, but in the case of an open jet tunnel the edge of the stream was distinctly "fuzzy." The open jet was, however, much more convenient in use.

Mr. W. L. COWLEY (National Physical Laboratory): He sympathised with Mr. Glauert in championing the cause of the 4 ft. tunnel on the ground that half a loaf was better than no bread at all, for he felt that constructors should do everything possible to obtain aerodynamic data by means of a tunnel of some description. At the same time, he felt that none would be content with half a loaf. A constructor who had a 4 ft. tunnel would before very long come face to face with problems which the 4 ft. tunnel could not solve, and that would lead to discontent. For example, the effect of airscrews was a very important problem, and he did not think that tests of models with airscrews running, in a 4 ft. tunnel, were really very satisfactory. Work had been carried out at Weybridge with airscrews of some 3 in. diameter, but one could not help feeling that such airscrews were not accurate to shape. In the development of methods of construction there were a number of things which could not be represented suitably in a 4 ft. tunnel but which could be handled more easily in a larger tunnel, and in view of the fact that the constructors were the people interested mainly in tunnels there should be more insistence upon the use of tunnels of larger size.

With regard to Mr. Glauert's diagram showing the results of tests on aerofoils of various aspect ratios, which diagram showed that the curve did not follow the turbulent boundary layer, he asked whether, in the course of those tests, Mr. Glauert had considered the effect of the turbulence in the tunnel. It had been said by Prof. Jones that the turbulence of the tunnel greatly affected the shape of the curves, and that if turbulence were created artificially it was possible for a good streamlined body to produce a curve very different from that which would be produced if turbulence were not created. It would be interesting to know what curves would be obtained if the aerofoils referred to by Mr. Glauert were tested in more steady tunnels.

Air-Commodore CHAMIER (Messrs. Vickers Aviation, Ltd.): He was completely undeceived by Mr. Glauert's very interesting lecture. One might almost think that Mr. Glauert had been put up by the Air Ministry to sell some more 4 ft. tunnels. He himself did not believe in the 4 ft. tunnel for the constructor, however. After experience one could get very good results in that size of tunnel when using sections which one knew and standard forms of construction, but when one changed the types of machines and forms of construction, wing sections, and so on, one sometimes obtained very sad results. When one was most likely to be at sea, namely, when changing patterns, the 4 ft. tunnel was likely to let one down badly. The problem was largely one of scale effect. Mr. Glauert had said that one could make enormous use of the tunnels by chopping up an aeroplane into little bits, testing the drag, and so on, of each bit, and adding the results together. In aerodynamics, however, if one added together five twos the result was not ten; it was always some other figure. Again, constructors had not time to play with the little twos; they wanted to test a complete model in a tunnel as quickly as possible and find out whether it was a good design or not. There were alternatives to 4 ft. tunnels. One might go out to America and pick out a first-class aeroplane and sell it to the Air Ministry, and then use one's experience of that to sell more aeroplanes to the Air Ministry. He knew of one firm who had received an order to build an interceptor fighter with an air-cooled engine, but when they had built it they had felt that it was a very unpleasant looking aeroplane. They had built another, with a water-cooled engine, and, according to the daily press, they were going to receive orders for another 300 or 400. Finally,

Air-Commodore Chamier emphasised that he was not against the use of wind tunnels, but considered that the best was the biggest.

Mr. HENRY DAVIES: When discussing the scope of different tunnels, Mr. Glauert had said that unless this information were already available, special tests in the compressed air tunnel would be required to determine the full-scale maximum lift coefficient. In spite of this, a serious discrepancy was sometimes found between the maximum lift coefficient as determined in the compressed air tunnel and in full-scale tests. In particular, the "Clark Y.H." section, when tested full-scale, had a maximum lift of only 0.51, whereas, when tested in the variable density tunnel in America, it gave a maximum lift of, he believed, 0.65. Mr. Davies asked whether Mr. Glauert could explain this discrepancy, whether he could say on which type of aerofoil one should look for the discrepancy, and, in the absence of full-scale tests, what type of tunnel results were going to help at all.

Mr. G. C. P. RUSSELL (Messrs. Handley Page, Ltd.): He would like to congratulate the lecturer on producing such an interesting and helpful paper. It is really very gratifying to hear some kind words spoken about the 4 ft. wind tunnel.

He was particularly interested in what the lecturer said about the effect of tunnel size on the maximum lift coefficients of wing sections. Apparently, the R.A.E. tests referred to by him indicated that the maximum interference is caused by the vertical sides and not by the top and bottom of the tunnel, whereas some tests made at the R.A.E. about two years ago on a slotted R.A.F. 28 Model indicated, he believed, that differences in maximum lift were caused by various tunnel depths, in other words by various changes in the distance between the top and bottom of the tunnel. However, they had to remember that in the case of the slotted wing, the angle at which the maximum lift is obtained is considerably higher than the test referred to by Mr. Glauert.

From what the lecturer has said it would appear that they had a fairly reliable tunnel constraint correction for a large model up to its normal stalling angle; from the R.A.E. tests carried out on a single slotted wing they had an approximate idea of the error in the K_L max. when measured in a 4 ft. tunnel. In view of all this he was wondering whether Mr. Glauert had in mind any correction that could be applied to the testing of large models at still higher angles of incidence, for instance, a multi-slotted wing at say 30° to 40°. Tests made on multi-slotted wings some ten or twelve years ago were conducted on 36 in. span × 6 in. chord models in a 4 ft. wind tunnel and, owing to the absence of any known corrections at this time, the results were looked upon as gospel. However, in the light of their present day knowledge, they knew that the values of K_L max. so measured were probably very much in excess of their true value. Therefore, unless some correction is applicable, there is little hope of obtaining successful results in this direction from the small wind tunnel, since it is quite impossible to manufacture a model such as mentioned above to scale less than 6 in. chord.

In connection with this type of test another point of importance is the measurement of the actual wind speed through the tunnel during test. If, for instance, a 36 in. span x 6 in. chord multi-slotted wing model is tested in a 4 ft. wind tunnel at say 35° to 40° incidence, it is obvious that a considerable choking effect will occur, and during one or two of the original experiments it was noticed that a considerable drop occurred in the chattock gauge reading when these angles were reached, although the gauge was coupled to a hole in the side of the wind tunnel at a point half way between the working section and the inlet cone. From this it would appear to be impossible to measure the effective airspeed through the tunnnel.

Communicated.—He felt that Mr. Glauert may have misunderstood his question to him. He quite agreed with him that without any trustworthy correction tests carried out on large models at very high angles of incidence would be a "sheer waste of time" *to-day*. However, at the time when the tests in question were conducted corrections of this kind were non-existent and he maintained that time was no more wasted then than it may appear to have been on some of the present-day Official Wind Tunnel tests in the light of the future.

Mr. REYNOLDS (Messrs. Armstrong-Whitworths): It seemed to him that the value of the results obtained in the 4 ft. wind tunnel could be gauged by comparing them with the results obtained in the duplex tunnel. If the agreement were fairly good, then the 4 ft. tunnel results could be regarded as fairly reliable. The majority of the manufacturers had at times had opportunities of testing their models in their own 4 ft. tunnels and also in a larger tunnel at the National Physical Laboratory, and no doubt they had made comparisons of the results. Whilst he was at the works of Messrs. Handley Page quite a number of models were tested in a tunnel there and also at the R.A.E. and N.P.L., and he believed that the lift and drag results agreed very closely. The tunnel at the works of Messrs. Sir W. G. Armstrong-Whitworth was of slightly different type; he had not been able to make a direct comparison of the results obtained in that tunnel and others, but hoped to be able to do so shortly. The whole point about these tests was to get a basis of comparison. Provided one knew what the error was in the tunnel, he believed one was fairly safe in making comparative tests. It was difficult at times to obtain absolute values, even in a large tunnel such as the duplex. As to the suggestion that the open jet type of tunnel might be the easiest type of tunnel for operation by a commercial firm, he suggested that one could have two sets of balances. By that means a larger number of tests could be carried out; one would be able to use the tunnel for double the length of time that one could use the ordinary tunnel with one set of balances. Mr. Reynolds took the opportunity to acknowledge the great help which had been afforded the manufacturers by the N.P.L. and the R.A.E. in connection with wind tunnel work, for he was anxious that an acknowledgment of that help should be placed on record. During the time the tunnel was being erected at the works of Messrs. Sir W. G. Armstrong Whitworth, the staff of the R.A.E. and the N.P.L. had rendered great assistance, and had been only too glad to give any information in their power to help to make the tunnel a success.

Mr. E. OWER (National Physical Laboratory): Mr. Glauert had made out a very good case for the use of the 4 ft. tunnel in testing wing sections and bodies of simple form, but he was not confident that the position was quite so favourable as regards tests of combinations of parts. Consider, for example, the case of the interference effect of a nacelle on a wing. Mr. Glauert had suggested that in dealing with problems of this kind the wing should stretch right across the tunnel, and he had also made the stipulation—a stipulation with which Mr. Ower agreed—that the span of the wing should be sufficient to include the whole area influenced by the interference of the nacelle. This consideration fixed the scale of the model and Mr. Glauert had rather given the impression that one could fulfil the requirement and still use a large enough model of the nacelle to reproduce faithfully most of the important engine detail and to be out of the region in which scale effect was serious. Mr. Ower was not sure, however, that this was in fact the case, judging from results he had recently obtained at the N.P.L. These showed that in certain positions the nacelle might affect the flow past the wing for at least 6 or 7 nacelle diameters on either side of the nacelle. It was, then, easy to see that the size of nacelle model that could be used in the 4 ft. tunnel was not really large enough to enable the data deduced by its aid to be confidently applied to full-scale design.

In connection with Mr. Glauert's discussion of the "choke" velocity, he would like to draw attention to an important theoretical contribution by Mr. Lock on this matter, which was recently published in the Reports and Memoranda of the Aeronautical Research Committee.* In this paper Mr. Lock has worked out the "choke" effect of streamline bodies of different shapes for tunnels of various sizes, and has shown how the results of drag measurements must be corrected to give the equivalent free air data.

Reply to Discussion

Mr. Glauert: He would like to deal first with the question of the choke correction. He had had no intention of suggesting that that method of representing interference velocity was a correct method; it was intended only as an illustration to show how bad the old choke correction was. A calculation of greater refinement, such as had been put forward by Professor Lamb for a particular type of body, would be necessary in order to determine what the real effect of velocity was, but, in any case, the old choke correction did fail.

With regard to the flat plate curves, referred to by Dr. Piercy, he said his impression was that there was some danger in drawing those curves and imagining that all bodies were going to conform to them. He really did not see any reason why they should; they might happen to agree in some cases, but the point he had wished to make was that there were good reasons for believing that an aerofoil would accomplish its transition at an earlier point than would the flat plate. Again, whereas the flat plate had purely a fractional drag, in the case of an aerofoil the factor of form drag also arose, which might neutralise the tendency to reduction of the pure friction drag.

He agreed, of course, that maximum lift could not be measured in a 4 ft. tunnel, but he believed that in regard to minimum drag it was a little more hopeful. He appreciated that there were difficulties, but such tests as had been made at the R.A.E. did indicate that a reasonable value could be obtained by tests of low aspect ratio wings, or by tests of wings completely across the tunnel. Dealing with the question raised by Mr. North as to whether the slope of the lift curve so obtained was satisfactory, he said the difficulty in that connection was to determine what standard to adopt. One would not necessarily get the theoretical value from any aerofoil, but certainly in recent tests at the R.A.E., comparing an aerofoil with an aspect ratio of about 4 in a 7 ft. wind tunnel and one stretched completely across the tunnel, agreement was obtained when corrections were made for aspect ratio and tunnel interference.

With regard to the question of the size of tunnel that should be used, his position was rather a difficult one. It was impossible to say that a 4 ft. tunnel was better than a 5 ft. tunnel, or that a 5 ft. one was better than a 6 ft. one; the larger the tunnel, the better. What he did want to point out was that certain types of tests could be carried out successfully in a 4 ft. tunnel.

Dealing with Mr. Russell's question as to the testing of a slotted wing set at 35° incidence, he said he did not know what the effective velocity was, and he did not think there was any value in the test. Any attempt to measure the maximum lift of an aerofoil of that type in a 4 ft. tunnel was waste of time; the 4 ft. tunnel was absolutely unsuitable for the experiment.

As to the discrepancies between compressed air tunnel results and full-scale results in America, if the wings were tested at the same Reynolds number, and if the tests were identical, someone had blundered. Probably, however, that was not the condition; probably a simple aerofoil had been tested in the compressed air tunnel, and a complicated aeroplane, with body, nacelles, air-screws, struts and wires had been tested on the full scale; it was necessary to

* R. & M. 1275. The interference of a Wind Tunnel on a Symmetrical Body.

make some analysis in order to find out the cause of the difference. The experimenters might have put on a body which spoiled the characteristics of the aerofoil, and the matter was clearly one for further investigation. He certainly did not believe that the ordinary law of scale effect had broken down, or that there was something peculiar in the aerofoil or in the air as compressed in America.

He agreed with Mr. McKinnon Wood that a suitable form of tunnel for constructors would be the return circuit type, and of the largest size that a firm was prepared to adopt. The power factor of the R.A.E. open jet tunnel was 0.4, and Mr. McKinnon Wood had pointed out that if it were made as a closed jet tunnel the power factor would be still lower. That answered to some extent Mr. North's question as to how, in the American tunnel, a low power ratio of 0.2 was obtained. He believed a further improvement could be made by sacrificing compactness and having a very slow expansion going on over a still greater length. That would involve, of course, a very long building. Presumably the ideal tunnel would be one which expanded very slowly for a very long distance and then came back, but that was not very convenient. He had been accused by Air Commodore Chamier of trying to sell 4 ft. tunnels, but that was not quite what he was trying to do. He would like to see manufacturers use wind tunnels as large as possible. If he had any hidden intentions at all, possibly they would be to persuade those who had wind tunnels to use them, and not to bring all the work to the compressed air tunnel and the large wind tunnel of the R.A.E.

CONTROLLABLE-PITCH PROPELLER

BY

W. R. TURNBULL, F.R.Ae.S.

Confusion has arisen regarding just what is meant by adjustable variable-pitch and controllable-pitch propellers, and the matter should be more clearly defined in the following way:—*Fixed-pitch propellers* to apply to both (*a*) the ordinary fixed-pitch propeller, made up with the hub and blades integral, and the material the same throughout, and (*b*) the detachable-blade or *ground-adjustable* type that will usually have the hub and blades of different materials, and in which the blades will be clamped in the hubs on the ground to an angle that is assumed, usually by experiment, to give the best general or some specially desired performance results. This type is obviously also fixed pitch as far as flight is concerned as soon as a certain angle is decided upon and set on the ground. The *variable-pitch propeller* has been used to designate both (*a*) a fixed-blade propeller, in which, by special design, the pitch has flattened out or increased according to the relative speeds of the airplane, or the engine, or both. A few have been built and used, but their advantages over the ordinary fixed-blade type have never been fully demonstrated. Of course, the variation in pitch occurs mainly in the tip sections only and does not affect the blade as a whole. We might therefore say that all fixed-pitch propellers are variable pitch, in this sense, to a slight degree, since none is a rigid structure. The term variable-pitch propeller has also been used to designate one having the blades movable about their radial axes, the blade angle being controlled by the pilot when the aeroplane is in flight; but owing to the two meanings that have been applied, I now believe that this second meaning should be dropped, and in this paper I use the term *controllable-pitch propeller* to mean one having the blades mounted in the hub, so that they can be turned about their radial axes during flight, and at the will of the pilot.

For the fixed-pitch propeller some condition of flight must be chosen by the designer on which to base his calculations, and that will usually be the top-speed when flying level at low altitude. For convenience in dealing with the angles of a controllable-pitch propeller I will call the angle so found, and at some definite radius, such as 36 or 42in., the " normal angle," and refer any other angle that the controllable-pitch propeller may be given by the pilot to this as plus, signifying a greater, and minus, a lesser pitch-angle than the " normal."

In the fixed-pitch propeller, assuming good design, the propeller will be just right for the case of top-speed level flying and full-open throttle, with the engine running at its normal rated number of revolutions per minute and the efficiency of the propeller will be the maximum for this one condition of flight. For any other condition of flight the propeller will be less efficient and the over-all efficiency of the airplane will decrease, and under some conditions to a very considerable extent.

In general, the efficiency of any given propeller will vary as v/ND, in which D = the diameter in feet, N = the revolutions per second, and v = the translational velocity of the aeroplane in feet per second, and the maximum value for a propeller is reached when the value of this ratio is in the vicinity of 1.0. The diameter D is usually fixed by the general design conditions imposed by the aircraft, and therefore the efficiency is usually a function of the speed of the ship and also of the speed of the engine, and thus cases often occur, when v is relatively low and

n relatively high, where a geared-down engine is indicated as the best method of obtaining a good efficiency from the propeller, while without the gear-down the efficiency would be really poor.

Once a propeller is built D becomes fixed, and since v/N is the pitch of the propeller, then this pitch must be varied, when n and v are varied, in order that the ratio v/ND may approach as nearly to 1.0 as possible.

Top Speed Case

High speed, or top speed when flying level, is the condition for which the fixed-pitch propeller is usually designed, and the designer aims to have his v/ND, for this condition, approach as nearly to 1.0 as the design conditions of the aircraft as a whole permit. The controllable-pitch propeller meets the condition just as well, but no better, than the fixed-pitch type at low altitude, but at great altitudes produces a marked improvement that will be discussed later.

Take-off

In usual cases the maximum thrust per horse-power occurs during take-off and when the speed of the aeroplane is in the vicinity of 15 to 20 m.p.h., but with fixed-pitch propellers, the brake horse-power of the engine is still down owing to the number of revolutions per minute even with full throttle. With controllable-pitch propellers, the maximum power of the engine can be attained by decreasing the pitch of the blades, usually 3 to 4 deg. below normal, and thus a very great advantage is gained, particularly in heavily loaded aeroplanes that would otherwise be unable to leave the ground.

To take a concrete case, a certain engine of the 200 h.p. class is down in horse-power about 15 per cent. in the early stages of take-off, but when the full horse-power is regained by decreased pitch of the propeller, we have the equivalent of 30 more in horse-power available, and since the thrust per horse-power is high, 5 lb. per h.p. or more, at just the critical speeds of take-off, we have an *additional* thrust of 150 lb. to get the machine into the air, when a controllable-pitch propeller is employed.

Climb

In no condition of flight are the advantages of a controllable-pitch propeller more apparent than during climb, and the improvement in this phase of performance that can be brought about, often by slight changes in the pitch of the propeller of a 2 to 3 deg. decrease below normal, is sometimes very remarkable. To illustrate the point, consider certain actual official tests, carried out at the Isle of Grain Air Station, England, Aug. 28, 1917. The machine was a Short seaplane, weighing 5,518 lb. and driven by a 240 h.p. Renault engine having a normal speed of 1,250 r.p.m.

This same seaplane and engine were tested with two fixed-pitch propellers that were almost identical, except that one had a pitch throughout the blade of approximately $2\frac{3}{4}$ deg. less than the other. Nine tests were made with the result that the propeller of lesser pitch gave rates of climb that were from 31 to 85 per cent. better, the average of all the tests being 60 per cent. In both cases the engine throttle was kept fully open, during the climbs, but, of course, in the case of the lower-pitched propeller, the revolutions were normal, 1,253 r.p.m., and the full power of the engine could be developed, but in the case of the other propeller, which was designed for the top speed of the machine and not for climbing, the engine speed was 1,230 r.p.m., or below normal, and the full horse-power could not be developed when climbing as can be readily understood. In addition to the cases cited above, and many like it, the advantages of variable-pitch propellers in climbing have been calculated out by Betts and Mettam* who

* See British Advisory Committee for Aeronautics Reports and Memoranda No. 577.

found that for an S.E. 5 machine with a Wolseley Viper engine, developing 212 b.h.p. at 1,900 r.p.m. a controllable-pitch propeller should increase the rate of climb 31 per cent. at 2,000 ft., 36 per cent. at 10,000 ft. and 70.5 per cent. at 15,000 ft. Their results are plotted in Fig. 1, and these should be capable of still further improvement with a supercharged engine.

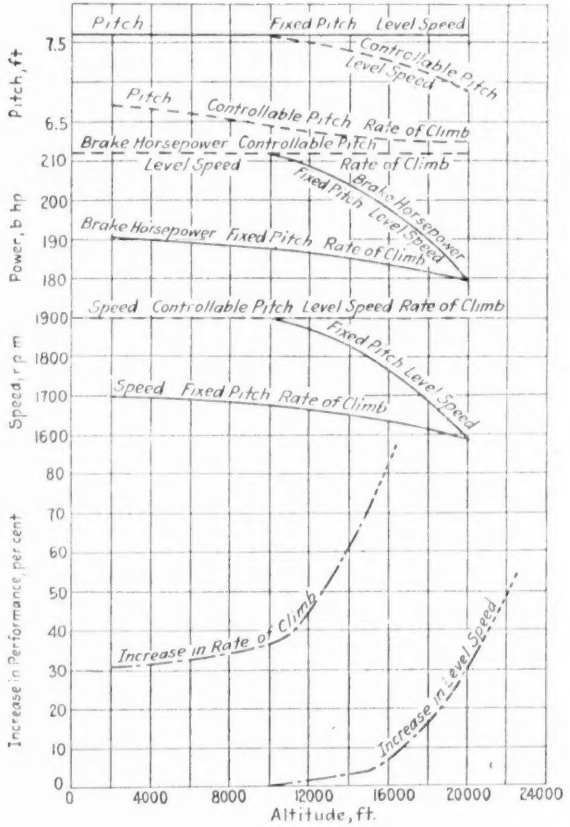


FIG. 1.

Comparison of a Fixed-Pitch and a Controllable-Pitch Propeller in Level Flight and in Climb.

These curves, which are reproduced from a British Advisory Committee for Aeronautics Report, show that for an S.E.5 aeroplane with a Wolseley Viper engine developing 212 b.h.p. at 1,900 r.p.m., a controllable-pitch propeller should increase the rate of climb from 31 per cent. at 2,000ft. to 70.5 per cent. at 15,000ft.

High Altitude Flying

In flying at great altitudes special conditions are met. The air density at 20,000 ft. is only about one half that at sea level, and to get full performance out of an aeroplane, both the controllable-pitch propeller and a supercharged engine are clearly indicated. The authors last cited have calculated the advantages

that would be gained by employing a controllable-pitch propeller without a supercharged engine, a gain of 30 per cent. in top speed at 20,000 ft. being indicated by their calculations. They also indicate a reduction of pitch, in the attainment of this result, whereas, the pitch probably should be *increased* beyond the normal, at the greater altitudes, if a thoroughly efficient supercharged engine were employed that could develop the full power of the engine, since the top speed of a machine should be greatly increased in the rarefied air, as its resistance goes down in proportion to the air density, and therefore the pitch of the controllable-pitch propeller should be considerably increased to comply fully with the condition of the higher velocity.

Best Cruising Speed

Since the term cruising is somewhat indefinite, we think the term " best cruising speed " should be employed and define this as the speed at which an aeroplane will travel the greatest distance with the least fuel consumption or, briefly, the best result in miles per gallon.

Several items enter the problem and complicate it. Chief among these is the fact that aviation carburettors are usually adjusted to give " best setting " at three-quarters to seven-eighth throttle whereas the ideal setting, for maximum economy, with a controllable-pitch propeller, would be a " best setting " at one-quarter to one-half throttle, if the aeroplane is to be used mostly at best cruising speed. If such adjustments were possible extremely high economies could be reached, and, in certain services, at least, this is desirable, for operation costs would be greatly reduced, not only on account of important savings in the fuel bill but also on account of lessened wear and tear on engines and the long periods between necessary engine overhauls. With an aeroplane really tuned, in all particulars, for travelling at best cruising speed, the engine speed will only be about two-thirds of the rated number of revolutions per minute, and engine life and the time between overhauls should be lengthened to a very remarkable degree.

To obtain some specific data on this question, the Curtiss Aeroplane and Motor Co. has carried out some tests. A detachable blade propeller, the pitch of which could be altered and set on the ground, was used. The aeroplane was a Curtiss Robin, and an auxiliary tank was so fitted that the exact time of using 1 gal. could be taken with a stop-watch. For each pitch setting the pilot went up to 2,000 ft. and then adjusted the throttle to just fly level, at the predetermined air speed; 76, 88 and 100 m.p.h. being the three speeds at which the tests were made. He then closed the petrol supply from main tanks, opened that from the auxiliary tank and with a stop-watch took the time required to use exactly 1 gal. During this run he also noted throttle opening and engine speed.

The results of these tests are plotted in Fig. 2, and while we propose to pursue the investigation considerably further, enough was learned to indicate the important saving in fuel that could be effected by using a controllable-pitch propeller, at a coarse pitch in the cruising case, even with a standard carburettor and with only the usual adjustment for making the mixture lean or rich. The curves indicate a best cruising speed of about 76 m.p.h. and this aeroplane, fitted with a controllable-pitch propeller, could therefore take-off well with a fine pitch setting, climb rapidly to a desired height, then change the pitch to a coarse setting and proceed at the best cruising speed and lean mixture.

For this latter case, 8 ft. pitch, the throttle opening was less than one-fifth, and the speed was only 1,150 r.p.m. against a normal 1,800 r.p.m.; while the fuel consumption was 1 gal. per 14 miles. How important the fuel economies and reduced engine wear and tear can become for certain services, even with carburettors as ordinarily adjusted, is at once obvious. The normal pitch for this aeroplane and engine is 5 ft. and at 76 m.p.h. the engine speed would be

1,450 r.p.m. The advantage, then, in using a controllable-pitch propeller instead of a fixed-pitch propeller, for this case, works out at a saving of 12 per cent. in fuel consumption and 26 per cent. in engine speed. With special carburettor adjustment, I believe that this result could be materially improved.

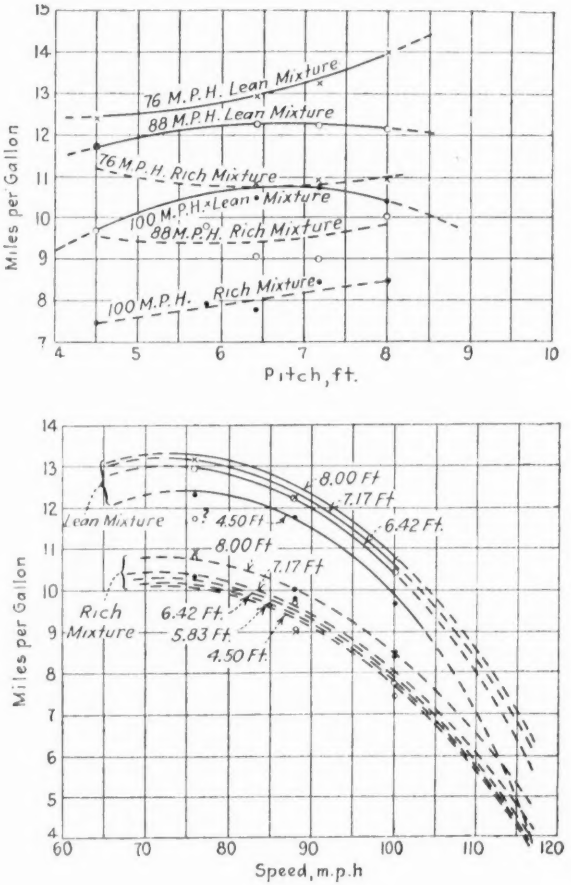


FIG. 2.

Pitch-Fuel Economy Curves.

These tests, which were made on a Curtiss Robin aeroplane equipped with a detachable-blade propeller at an altitude of 2,000ft. and speeds of 76, 88 and 100 m.p.h., showed that the best cruising speed was 76 m.p.h. and that the best pitch was 8ft. The throttle opening under these conditions was one-fifth. The speed was only 1,150 r.p.m. as compared with a normal rate of 1,800 r.p.m., and the fuel consumption was 1 gallon per 14 miles.

Supercharging

The supercharged engine has given abundant proof that it is capable of greatly increasing the performance of an aeroplane, particularly with respect to the climb, ceiling, and level top speed flying at great altitudes, and a super-

charged engine can be made to develop 10 to 20 per cent. more power at 20,000 ft. than it will at sea level. It has, however, a serious disadvantage, when used with a fixed-pitch propeller on the question of take-off and early climb, since to utilise its extra power at great altitudes, it must be overloaded by a propeller that is too steeply pitched at the ordinary altitudes near sea level.

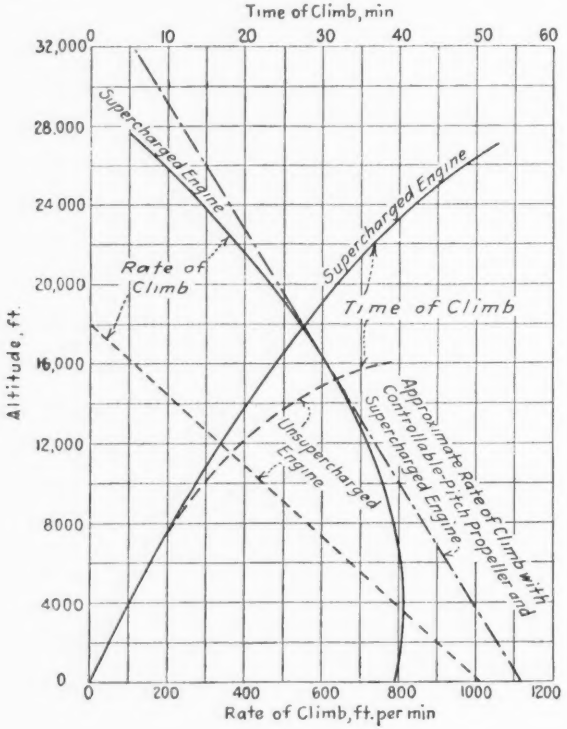


FIG. 3.

Effect of Supercharging upon Climbing Rate and Time of an Aeroplane Equipped with a Fixed-Pitch Propeller.

Supercharged performance is shown by the full lines and unsupercharged by the dotted lines. These curves show that up to 4,000ft. the unsupercharged engine gives the better rate of climb, which has an important bearing on the take-off. The approximate rate of climb with a supercharged engine and a controllable-pitch propeller, the pitch of which could be reduced for early take-off and climb and increased beyond normal in the latter stages of the climb, is included.

A typical case of an aeroplane having a propeller of the fixed-pitch type, with and without a supercharged engine, is shown in Fig. 3. Full lines show the supercharged engine performance, while dotted lines show the unsupercharged engine performance, and up to 4,000 ft. the unsupercharged engine gives the better rate of climb, and this, therefore, has an important bearing on the take-off. With a controllable-pitch propeller, the pitch could be reduced for take-off and early climb, while in the latter stages of the climb it could be increased beyond normal (see Fig. 4) and we should then have an aeroplane capable of better take-off and early climb and capable of still better performance at great altitudes than

the remarkable improvement already shown for the supercharged engine with a fixed-pitch propeller. While the case has not been carefully calculated, we should then expect for the supercharged engine coupled with a controllable-pitch propeller, a performance curve similar to that marked Approximate Rate of Climb with Controllable-Pitch Propeller in Fig. 3. A full appreciation of the supercharged engine has really been awaiting the development of a thoroughly satisfactory controllable-pitch propeller since the two mechanisms are complementary to one another and some very remarkable improvements in performance can certainly be attained when the two are used in conjunction.

In future flying, in accordance with the argument just set forth, a line of development can easily be foreseen by which machines will no longer fly near the sea level, but will ascend to great altitudes and fly there at a much greater speed than any heretofore attained, with the expenditure of no more fuel than they would use near sea level. Such a development might not mean very much for the general transportation of passengers, who might suffer from the physiological

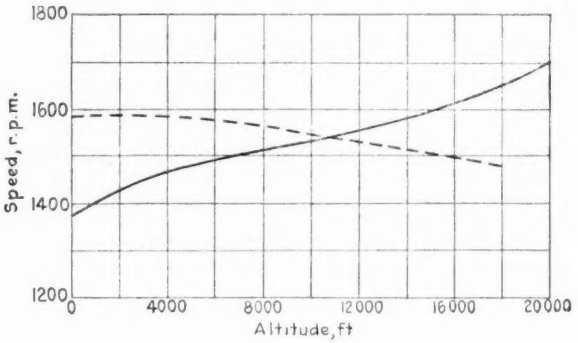


FIG. 4.

Speed-Altitude Curves for a Controllable-Pitch Propeller and a Supercharged (Full Line) and an Unsupercharged (Dotted Line) Engine.

effects of flying beyond 10,000ft. unless air-charged sealed cabins are simultaneously provided, but in military flying and the transportation of mail it could mean considerable, since young pilots who become accustomed to flying find no difficulty in flying at an altitude of 15,000 or 20,000 ft., as was proved during the war.

For such a service the aeroplane would be equipped with both a supercharged engine and a controllable-pitch propeller, the pilot would take off better than with an ordinary machine by reducing his pitch several degrees below normal, and make the early climb with the same setting. When he had gained altitude he would gradually increase his pitch and hold the speed constant in this way (see Fig. 4) until at 20,000ft. he would flatten out and go off on his course at a very much greater speed than he could have attained near the ground level, and at, possibly, double the speed near the ground when the fine points of the case are all worked out.

Multiple Power Units

With an aeroplane having more than one power unit we must consider principally the case of the accidental stoppage of one or more engines. How serious this may be will depend mostly on the number of units employed. If the machine

contains four units and one stops, the pilot will still have three-fourths of his total power left; if the machine has three units, he will have two-thirds of his power left; and if it has two units, he will have one-half his power left. This will be strictly true *only if the machine has controllable-pitch propellers,* for if the propellers are of the fixed-pitch type, the moment one unit stops a double loss occurs, since the aeroplane will then have one or more engines still going but with wrongly pitched propellers and one or more dead engines with stopped propellers, the blades of which will add very considerably to the total resistance of the aeroplane and thus further reduce the speed.

In the case of engine failure in one unit of multi-engine aeroplane not only will it have lost completely the power of one engine, but the power of the other engines will be reduced since the pitch of their propellers will no longer be correct for the reduced air speed. The live engines will slow down and be unable to develop their full power, while, moreover, the stationary propeller on the dead engine will contribute a large item of parasitic resistance, 40lb. in the case of a 9ft. propeller at a speed of 60 m.p.h., to which we might assume the speed of the machine has been reduced by reason of one propeller being stopped.

If, on the other hand, the ship is provided with controllable-pitch propellers and one engine stops, the pitch of the propeller on the live engines can be reduced, so that the engines can be run at their proper speed for maximum power, and thus get a much increased thrust from these engines and propellers. The pitch of the propeller on the dead engine can be swung into a feathering position, in which the average attitude is one that is nearly edge-on, and thus the parasitic resistance can be reduced to the minimum. The quantity of fuel that would have to be jettisoned would be much less, depending on the stage of the journey, and the journey could be continued with only a small reduction of the obtainable range, although the speed might be considerably decreased.

Heavy Loads

With heavily loaded aeroplanes, intending to make long-distance flights, and also with flying boats, which sometimes find it difficult to attain the proper planing speed, the controllable-pitch propeller is very clearly indicated as a necessity. Several contemplated long-distance flights with both of these classes of aeroplanes have had to be abandoned, due to the inability of the machine to leave the ground. Assuming 45 m.p.h. as the take-off speed of an average case of this kind, we find that with a fixed-pitch propeller we could expect a thrust of 4.7 lb. per h.p., whereas with a controllable-pitch propeller we could properly expect a thrust of 6.1lb. per h.p., or an increase of 30 per cent. in the available power to get the aircraft off the ground.

Gear-down

A tendency of growing importance is that towards the installation of a geared-down engine for cases in which the air speed is moderate but the engine speed is high. The controllable-pitch propeller offers no special advantage for such cases, but designing controllable-pitch propellers to meet them is somewhat easier than it is for the high-speed direct-connected cases, since the centrifugal forces will be considerably less at the lower speed. In general, the efficiency of both the fixed-pitch type and the controllable-pitch type of propeller will be considerably improved, in such cases, owing to the increase in value of the ratio v/ND.

The Problem of Design

Designing and building controllable-pitch propellers is admittedly difficult, and had this not been so, they would have come into general use many years ago, since some at least of the advantages of controllable-pitch propellers were known

as early as 1910, when the question appeared in aeronautic literature. The three chief difficulties that the designer encounters are (*a*) the excessively high centrifugal force acting on the blades—an all-metal blade weighing 27lb. will impose a centrifugal load of over 20 tons at the hub at 1,900 r.p.m.; (*b*) the friction conditions obtaining with such a load and also those from the aerodynamic thrust loading; and (*c*) a control for altering the blade angles, which will neither be too slow nor too fast in its action and yet will allow the pilot to make the necessary settings with the minimum trouble and exertion. In addition to these we have the following points to consider and to meet:—

(1) Low weight.
(2) Reliability.
(3) Freedom from wear.
(4) Operability at reasonable engine speeds.
(5) Pitch-indicating devices.
(6) Independence of pitch-control mechanisms.
(7) Safety.

Weight

The weight of the design should be kept to the minimum. The advantages in performance which the controllable-pitch propeller offers will certainly offset a reasonable increase in the weight over the fixed-pitch type, but at the same time this increase must be so moderate that neither the pilot, nor the designer of the aircraft, will be prejudiced against the controllable-pitch propeller as a type. In case of accident, substituting a fixed-pitch propeller when another controllable-pitch propeller is not available without much alteration in the trim and controllability of the aeroplane also should be possible.

Reliability

The mechanism controlling the pitch should be reliable in its action at all times. In ordinary flying, particularly under cruising conditions, the pilot will not need to alter the pitch, except occasionally. In taking off in a restricted space or with heavy load and in climb he may, however, have to make frequent changes until he settles down to his level-flight conditions, and the mechanism should always be ready to render the service that he will soon learn to expect.

Wear

In a controllable-pitch propeller the wear due to the operation of the blades would be relatively small, since the pilot should only make pitch changes when definite changes in flight conditions are indicated as necessary by the performance data and by his own experience with the aeroplane in attempting to attain the best performance. The most serious source of wear would probably be from blades having an inherent tendency to flutter, since a flutter would cause alternating loads of high frequency. The designer should therefore attempt to eliminate this by designing the blades so that the torsional moment on them is constant in direction.

Operation

The mechanism should be operable at reasonable engine speeds, and in general this will usually mean easy operation when the number of revolutions per minute is low, and more difficult when it is high. From one point of view, arranging the control so that the pilot cannot get operation at an excessive engine speed is a safety feature. For instance, when reducing the pitch angle the pilot may overspeed his engine inadvertently, and then the pitch control should cease

to function until the pilot realises the mistake he is making and throttles down his engine until the permissible speed has been reached. With some types of controllable-pitch propeller the pitch control can be connected with the throttle, so that the pilot will automatically throttle when reducing pitch, but at all other times the throttle will be independent of the pitch control.

Indicators

A pitch-indicating device that will inform the pilot of the change in pitch that he is producing is usually possible and in general is desirable. While the tachometer gives information on this particular point, when the pilot is changing the pitch, provided he does not also change the engine speed at the same time, nevertheless he may not change the pitch for long periods, and he should know his pitch setting before making a change and during its accomplishment.

In the case of engines that have failed the pilot should know his pitch setting, and this he can do only when the pitch-indicating device is entirely independent of the engine and the tachometer. In controllable-pitch propellers that are capable of giving the blades, on a dead engine, a feathering position, this has special significance, for in this case, certainly, the pilot should know just what he is doing to the pitch angle. This he could only know by an entirely independent indicator.

In nearly all the earlier forms of controllable-pitch propeller the designer very naturally sought to extract a little power from the engine itself to change the blade angle, but practically all devices of this kind have been wanting in one or more essential features of a controllable-pitch propeller. Usually trouble has been experienced from shock when such devices have been employed, and practically always, when a braking device has been used, the action of the blade-control mechanism has been so rapid and at the same time so uncertain that a fine setting of the desired angle has been hopeless or too lengthy in operation to be practicable.

A control that is entirely independent of the engine has the very great advantage that it can be still used on a dead engine, if the mechanism permits, to turn the blades into a feathering position. If the engine has stopped from some minor trouble that can be corrected during flight, the blades can be placed at an angle, say 45°, which is most advantageous for recranking the engine during flight.

The safety accessories that a controllable-pitch propeller should have is a question more or less open to discussion. Some engineers will hold, and perhaps properly, that the pitch control should be linked with the throttle control so that the pilot can never over-speed his engine. With limiting permissible engine speed, this is a device that can, and perhaps should, be employed with some types of controllable-pitch propeller, more for the sake of the engine than for the propeller.

The only other accessory that seems to be practically indicated is one for automatically limiting the range of the angle change and any chance of jamming the mechanism at its extreme limits of range or elsewhere. Some controllable-pitch propellers allow for this in the design and some do not. When they do, it is an undoubted foolproof feature of considerable value.

That the strength should be adequate and with good factors of safety goes without saying, and yet the controllable-pitch propeller certainly presents a nice problem in keeping weight down while stepping strength up. This has always been one of the serious difficulties in obtaining a practical controllable-pitch propeller, but much can be done by a clever proportioning of parts, and more will be done when systematic and considerable development occurs.

Centrifugal loads are always high in aeroplane propellers, and as they are in proportion to the square of the revolutions per minute, they are particularly

high with modern engines that run at 1,800 to 2,400 r.p.m. An average 200 h.p. engine with a 9 ft. all-metal propeller at 1,800 r.p.m will have a centrifugal load at the root of the blades of 35,000 to 40,000 lb., whereas the aerodynamic thrust load on one blade will probably be approximately 300 to 350 lb., so the magnitude of these two loads is about in the proportion of 100 to 1.

However, in the case of a controllable-pitch propeller, we have to deal with an articulated duralumin blade within a steel hub and the major part of the centrifugal load will be carried on the inner part of the hub, while the major stress, due to the aerodynamic thrust load, will come on the outer part of the hub. In the inner part of the hub the stresses per square inch due to the centrifugal load will run about five times as high as those due to the thrust-bending, whereas, in the outer part, the stresses due to the thrust load will be running about five times as much as those due to the centrifugal load, which is then only the centrifugal load of the outer part of the hub itself. This provides something of a problem in hub design.

In general, the uniform engine-torque on the hub portion of a controllable-pitch propeller design will produce stresses that are only about one-half those due to thrust-bending. We now have means of offsetting stresses due to thrust and torque, and bending due to centrifugal force, when this exists, as it does in some designs, in such a way that sections can be reduced and considerable weight be thus saved.

Torsional force on the blade is difficult to calculate, for the velocity at which aeroplane propellers usually run. Adopting such blade sections and plan form as will insure the torsional force being unidirectional is advisable, since this is conducive to minimum flutter and long wear.

Materials of Construction

Unless the controllable-pitch propeller is made of some uniform material throughout, such as wood with steel bearings and reinforcements, the hub portion will almost certainly be of steel, due to the high tensile-strength values, 150,000 lb. per sq. in. and upward, that are now obtainable with correct heat-treatment. This material thus lends itself to compact design and lightness and practically perfect fitting, without wear, on the engine shaft.

Materials that can be used for blades are listed in Table 1, together with data on their weights in pounds per cubic foot and in relation to wood, which is taken as 1.

TABLE 1.—WEIGHT DATA ON VARIOUS AEROPLANE PROPELLER BLADE-MATERIALS.

Material.	Weight, lb. per cu. ft.	Relative Weight.
Wood*	42.0	1.000
Micarta	85.6	2.040
Duralumin	175.0	4.175
Steel	490.0	11.650

* American black walnut.

Wood has been often used in the past for controllable-pitch propellers with various devices for (*a*) entering metal reinforcements within the blade which can also act as bearing members, or (*b*) clamping members that, being external to the wooden blade end and enclosed in a hub, severely compress the wood and also act as bearing members. The difficulty of making proper joints between wood and metal is the chief drawback of wooden blades. It has been successfully done, on both systems mentioned above, for moderate-speed engines, but neither

would likely be successful for high-speed engines for which, in general, wooden propellers are not suited.

Micarta might be suitable for geared-down engines and for high-speed propellers in the lower horse-powers. While it is attractive for controllable-pitch propellers on the questions of weight and centrifugal force, it has, however, not been very successful for large diameters and high speeds. The tendency toward duralumin blades in steel hubs has grown rapidly and, for the present at least, the controllable-pitch propeller is practically constrained to follow along the same lines of development.

Steel is not likely to displace duralumin for blades in the near future, although it might eventually, and so might magnesium alloys. For very large propellers and certain types of design steel proves lighter than the corresponding duralumin blades. Some radically new ideas in steel construction will have to be developed, however, before this can be generally true in all sizes.

History of Development

A complete history of the various types of controllable-pitch propeller cannot be attempted in this paper, but comments are given on those types that have received more than passing attention and development and differ in types of mechanism.

Hand Control

As a type of mechanically controlled propeller, the original Hart propeller of 1920 with its subsequent development and modifications running over 9 years, probably affords the best example. The design is now generally known as the Wright Field and a very serious effort has been made by many minds to convert the original idea of Mr. Hart into a thoroughly practical controllable-pitch propeller. The original design had wooden blades, a later design micarta blades and the latest designs duralumin blades, a sequence of much interest on the general tendency of development. In the early types the weakest point was the small size of the ball bearings that had to be used, and an undesirable feature was the restricted range that the type of design compelled. In later designs, we understand these matters have been improved, but the present design seems heavy and expensive to manufacture. The control is by a handwheel in the pilot's cockpit, operating through a series of shafts, gears, cams and levers.

Brake Control

With mechanical devices employing brakes, the idea of the inventor has been to let a small fraction of the engine power turn the blades by mechanical brakes checking a certain portion of the mechanism and thus producing rotation of the blades about their axes through brake wheels and appropriate gears connected thereto. This is a very natural idea, and we have examples in the early type Turnbull, the Paragon, the Sperry, the Curtiss-Moore and some others. Practical experience with this type has shown, however, that in some cases we have shock and other mechanical troubles and we also have a control that may be too uncertain in its results when the propeller is placed in the hands of the average pilot. The action of the mechanism is frequently too rapid and irregular, and the pilot must repeatedly advance and retard his pitch and lose considerable time in making the very small changes, of usually only a degree or two, which are those most frequently required in the use of a controllable-pitch propeller.

Hydraulic Control

The best known example of this type of control is the Hele-Shaw Beacham, a product of two English engineers, that was described at a meeting of the

Royal Aeronautical Society* in 1928. A description of the operation of this mechanism is too lengthy to be given here. In general the pitch of the blades is varied by a double-acting hydraulic piston operated by oil pressure from an adjustable-stroke pump driven by the engine. The stroke of the pump is in turn controlled by a governor, also driven by the engine, so that whatever the air conditions may be the pitch of the propeller sets itself so as to keep the engine running at a constant predetermined speed.

While the speed at which the governor operates can be altered by the pilot, within certain limits, by a small control lever, I think that automatically running at constant speed is wrong and that the wholly successful controllable-pitch propeller must leave the pilot free to adjust both the pitch, and the speed, to obtain best efficiency in the various conditions of flight.

A question regarding the durability and reliability of the mechanism might be raised concerning the action of the running joint for transmitting the oil under high pressures and long service. Data on service operation are lacking but tests are now being carried on in England by the Air Ministry. As the weight shows an increase of about 80 per cent. over a duralumin propeller of ordinary type† this leaves much to be desired on that score.

Electrical Control

In the earliest type of the Turnbull propeller, which was developed in 1916, the construction was a composite one, with wooden boss and blades, bronze sleeves and ball-thrust washer incorporated in the blades and a steel spindle incorporated in the boss. Control was by brake wheels and a gear train from these to a wormwheel segment on the blades and electro-magnetic drag brakes. These brake wheels showed too much lag and had to be abandoned in favour of mechanical brakeshoes, which in turn were abandoned since they introduced shock troubles and irregular action.‡ In June, 1923, after much experimenting with various types of control, an electric motor to be mounted on the end of the engine shaft, with gear-downs to the propeller blades, was adopted, and in 1927 this type of controllable-pitch propeller was given various tests, at Camp Borden, Ont., and worked to the full satisfaction of the Army pilots. Seven different pilots handled the propeller and 32 flights were made, when the propeller was disassembled for inspection and found to be in good order.

Realising that the tendency in design was distinctly toward the all-metal propeller, the Curtiss Aeroplane and Motor Co., in 1928, took up the further development of the Turnbull propeller and has met with some very promising results. The propeller is now designed with a duralumin blade extending into a steel hub and with this constructon a very rugged ball-thrust washer can be introduced to carry the high centrifugal load of the blades, while the design can be kept compact and light.

To get fine adjustments of pitch angle and to enable a very small electric motor to handle the centrifugal and thrust loadings, reduction gears having a ratio of 48,000 or 64,000 to 1 are used, which gives the pilot about the correct rate for blade-angle changes, 2 to 3 sec. of time for 1 degree of angle. Besides the really essential feature of slow and fine blade-angle adjustments and ready means of power transmission through brushes, the adoption of electricity lends itself to the introduction of any indicating and automatic safety devices that may be desired. Since, also, the control is entirely independent of the engine operation the blades of the propellers on a multi-engine aircraft can be swung into a feathering position on a dead engine, and, where desired for dirigible

* See Journal of the Royal Aeronautical Society, July, 1928, p. 525.
† See Journal of the Royal Aeronautical Society, July, 1928, p. 539.
‡ This early composite propeller is now exhibited at the Science Museum, South Kensington.

work, or the like, the propeller can be reversed while the engine rotation continues to be unidirectional.

An objection may be raised to the necessity of carrying a storage battery, due to its weight of about 16 lbs., but in aircraft that are likely to carry controllable-pitch propellers such a battery is already carried for radio, lights, and other uses, and the power for the motor can be taken from it. In the first all-metal Turnbull propeller, the 200 h.p. class at 1,800 r.p.m., the weight of all rotating parts was 128 lb., but in the second design of this class the weight had been reduced to 107 lb., and future designs probably will not run much over 20 to 30 per cent. greater than the weight of the corresponding fixed-pitch types.*

In the Turnbull type of propeller the range of the angle change is not limited and any desired range can be incorporated in the design. All requirements, as we now understand them, can be met by the Turnbull propeller. The tests on performance are in accordance with theory, and those on strength, endurance, wear and operation have been very satisfactory.

Conclusion

In the early days of aviation, the desirability of the controllable-pitch propeller was recognised, but with the advance in the art, desirability is rapidly changing the necessity since aeronautic engineers now realise that they *must* have controllable-pitch propellers to develop the full capabilities of the airplane as an established means of transportation.

If the added weight can be kept reasonably low, the great advantages in performance resulting from the use of a propeller that will give good efficiency at all conditions of flight, and also allow the full power of an engine to be developed when most needed, will offset many times the disadvantage of a heavier propeller.

Greater efficiency of flight will effect a large saving in fuel and the use of controllable-pitch propellers will also result in longer engine life and avoid the necessity for frequent engine overhauls. On these heads the added cost of controllable-pitch propellers should be soon made up in a few hundred hours of operation.

Considering the foregoing and in view of the special considerations previously mentioned, and which are coming more and more to the front, all the time, we must get the controllable-pitch propeller problem settled in a practical and satisfactory way and controllable-pitch propeller production seems essential.

Of the various types of controllable-pitch propeller described, we very naturally feel that the type using electric-motor control has the most promise, especially as samples of this type have been successful, both in actual flight and in withstanding rigorous test-stand operation.

Inevitably the next few years will see the extensive use of the controllable-pitch propeller on aeroplanes of many types and on practically all aeroplanes of certain types.

* During 1930 the Curtiss Company has built propellers with this control for 225 h.p., 450 h.p. and 600 h.p. engines.

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The Council wish to place on record their great appreciation of the work done by members of the various Committees of Council. It is through these Committees that much of the administrative and other work of the Society is done, and membership of such Committees often means a considerable sacrifice of leisure time to those serving.

Membership

In the last Council Report the Council expressed the opinion that many in the Royal Air Force and the Industry are not members of the Society who should be, and they wish to repeat this opinion. The effect of the new rules which came into force on 1st January, 1928, has been very considerably to stiffen the conditions for technical membership. The rules have been very carefully followed, with the result that the standard of technical membership is now such that it is being recognised as an important qualification when applying for a post in the industry. An Education and Examinations Committee of the Council is now sitting, and considering, in the light of the experience gained, a revision of the syllabuses of the Society's examinations, and of the list of exemptions from it. The tendency is for the examination standard to be raised still higher so that technical membership of the Society will, in the near future, be practically speaking an almost necessary qualification in the profession of aeronautics.

The membership of the Society continues to show a steady progressive increase. In the table is shown the figures of membership as on 1st January, 1931. The figures in brackets refer to the corresponding membership on 31st December, 1929.

	No. of Members.		Hon. & Life Members.		Suspended.		Total.	
Fellows	114	(108)	20	(18)	—	(2)	134	(128)
Members	38	(57)	—		5	(3)	43	(60)
Assoc. Fellows ...	394	(358)	5	(5)	9	(18)	408	(381)
Assoc. Members ...	88	(99)	—		12	(17)	100	(116)
Associates	142	(135)	2	(2)	16	(18)	160	(155)
Companions ...	143	(129)	15	(15)	6	(14)	164	(158)
Founder Members	33	(35)	—		1	(—)	34	(35)
Students	238	(179)	—		12	(35)	250	(214)
Tem. Hon. Members	—		23	(22)	—		23	(22)
	1190	(1100)	65	(62)	61	(107)	1316	(1269)
Less Joint Members	29	(30)	—		—		29	(30)
	1161	(1070)	65	(62)	61	(107)	1287	(1239)
Branches:—								
Australia	35	(31)	—		—		35	(31)
Bristol	135	(135)	—		—		135	(135)
Coventry	206	(200)	—		—		206	(200)
Gloucester & Cheltenham	137	(—)	—		—		137	(—)
Halton	—	(1500)	—		—		—	(1500)
Leeds	100	(100)	—		—		100	(100)
Manchester ...	120	(40)	—		—		120	(40)
Oxford	180	(180)	—		—		180	(180)
Yeovil	350	(350)	—		—		350	(350)
	2424	(3706)	65	(62)	61	(107)	2550	(3889)

The Cambridge University Aeronautical Society, which has a membership of about 300, is affiliated to the Royal Aeronautical Society. The drop in the

Branch membership is due to the dissolving of the Halton Branch for Service reasons.

Endowment Fund

The Endowment Fund of the Society aims at providing the Society with a suitable building including a lecture hall of its own and sufficient income for its upkeep. The first aim is the provision of a permanent income which will enable the Council to legislate ahead for carrying out, to a greater extent than is at present possible, the work for which the Society exists. It is not fully realised that the income of the Society from its members and investments is nearly £1,000 a year less than the present expenditure, despite the percentage decrease in overhead expenses during the past five years. There has, with increased membership, been a steady increase in printing costs, in the cost of upkeep of the library, and the increased number of lectures. The deficit between income and expenditure is at present largely made up by generous grants of £250 a year each from the Air Ministry, the Society of British Aircraft Constructors and the Society of Motor Manufacturers and Traders. But these contributions cannot be considered to be permanent in any way, and when they are no longer available the Society may be compelled to curtail many of its activities, instead of extending them.

At Christmas, 1930, an appeal was circulated to all members to contribute within their means to the Fund. The whole of the heavy expenses of this appeal has been borne by the President, Mr. C. R. Fairey, without whose generous help it would not have been possible to make it in the form it was made. The Council wish to impress upon all the members of the Society that, to quote from the appeal: "the real value of the Society's work must always depend upon the energy, the loyalty and the mutual co-operation of its officers and members."

The table below shows the progress of the Fund:—

	£	s.	d.
December, 1926	575	0	0
December, 1927	597	2	0
December, 1928	1,047	18	0
December, 1929	1,077	6	0
December, 1930	1,265	10	0

The Council wish gratefully to acknowledge the following first series of donations to the Fund. The list of donations is printed in the order received.

	£	s.	d.
J. Suthering, Esq., A.R.Ae.S.I.	5	0	0
Capt. I. T. P. Hughes, Q.R.R., A.R.Ae.S.I.	1	0	0
J. Selfridge, Jr., Esq.	5	0	0
F/O. D. V. Ivins, R.A.F., A.R.Ae.S.I.	2	0	0
F. R. Simms, Esq., M.I.Mech.E., M.I.A.E., M.I.Ae.E. ...	10	0	0
H. J. Mackintosh, Esq., A.F.R.Ae.S.	1	1	0
C. E. Oake, Esq., A.R.Ae.S.I.	1	1	0
H. H. Schonburg, Esq., A.F.R.Ae.S.	2	2	0
M. Shadwell Hooper, Esq., A.F.R.Ae.S.	5	5	0
British Aviation Insurance Group *via* Capt. A. G. Lamplugh, F.R.Ae.S., M.I.Ae.E.	26	5	0
J. Saycatch, Esq., M.I.Ae.E.	1	1	0
R. B. Winn, Esq., Stud.R.Ae.S.I.	1	0	0
Miss G. Cottrell, Comp.R.Ae.S.I.	1	0	0
Carried forward	61	15	0

	£	s.	d.
Brought forward	61	15	0
Professor C. F. Jenkin, C.B.E., LL.D., M.Inst.C.E., F.R.Ae.S.	10	0	0
Group Capt. H. M. Cave-Browne-Cave, D.S.O., D.F.C., F.R.Ae.S.	10	10	0
T. W. Willis, Esq., M.I.Ae.E.	1	1	0
A. D. Thurston, Esq., D.Sc., M.B.E., F.R.Ae.S., M.I.Ae.E.	1	1	0
F/O. F. Whittle, A.R.Ae.S.I.		10	0
T. S. Lofthouse, Esq., A.R.Ae.S.I.	1	1	0
J. Lauriston Lewis, Esq.	5	0	0
Sqdn.-Ldr. M. E. A. Wright, A.F.C., A.F.R.Ae.S.	21	0	0
J. F. Cuss, Esq., Stud.R.Ae.S.I.		5	0
Messrs. Myers and Co.	25	0	0
F. W. Westley, Esq., Stud.R.Ae.S.I.	1	1	0
E. C. Gibbons, Esq., A.F.R.Ae.S.	1	1	0
R. C. Sherriff, Esq., Stud.R.Ae.S.I.		10	0
F. A. Kerry, Esq., B.Sc., A.F.R.Ae.S.		10	0
F. G. T. Dawson, Esq.	50	0	0
Miss H. M. Lyon, M.A., F.R.Ae.S.	1	0	0
The Hon. Lady Bailey, D.B.E., A.R.Ae.S.I.	2	0	0
Prof. W. Pawlowski, F.R.Ae.S.	10	0	0
Comdr. L. D Macintosh, D.S.O., A.F.R.Ae.S., R.N.	1	1	0
Prof. T. H. Turner, M.C., A.R.Ae.S.I.	1	1	0
Charles Crisp, Esq.	10	0	0
Major T. M. Barlow, F.R.Ae.S.	5	0	0
E. J. Fearn, Esq., A.F.R.Ae.S.	1	1	0
L. W. Bryant, Esq., F.R.Ae.S.	5	0	0
T. A. S. Lloyd, Esq., Comp.R.Ae.S.I. (" Icarus ")		10	6
K. W. Marshall, Esq., Stud.R.Ae.S.I.		10	0
J. R. Ashwell-Cooke, Esq., Comp.R.Ae.S.I.	2	2	0
The Brook Tool Mfg. Co.	10	10	0
Capt. R. A. Tarleton, M.I.A.E.	5	0	0
J. W. Copley, Esq., A.F.R.Ae.S.		10	6
W. L. Avery, Esq., Comp.R.Ae.S.I.	2	2	0
Messrs. Bruntons	10	10	0
Messrs. Aluminium (II) Ltd.	5	5	0
J. C. Stevenson, Esq., A.F.R.Ae.S.		10	0
Sq.-Ldr. D. Lucking, A.F.R.Ae.S.	2	2	0
Central Chemicals, Ltd.	2	2	0
A. J. Henington, Esq., A.M.I.Ae.E.	1	0	0
The Ealing Park Foundry, Ltd.	5	5	0
Messrs. Burley, Ltd.	5	5	0
L. G. S. Reynolds, Esq., O.B.E.	1	1	0
Messrs. Everett & Co., Ltd.	21	0	0
The Barnes Aluminium & Bronze Co.	5	5	0
J. Johnston, Esq., A.F.R.Ae.S.		10	6
High Duty Alloys, Ltd.	10	10	0
Major C. J. P. Ball, D.S.O., M.C. A.F.R.Ae.S.	21	0	0
J. Halden & Co., Ltd.	5	5	0
Total acknowledged	£344	4	6

The Council also wish to record their thanks to Messrs. Gale & Polden for a contribution of £18 9s. 6d., representing a percentage of the profits from all copies sold of the Aeronautical Diary.

Donations

The Council wish to record their thanks to the Air Ministry, the Society of British Aircraft Constructors and the Society of Motor Manufacturers and Traders for their generous contributions of £250 a year each to the Funds of the Society. This is the sixth year in succession the grant has been made by the Air Ministry and the Society of British Aircraft Constructors, and the third year by the Society of Motor Manufacturers and Traders. The Council's special thanks are due to Mr. H. E. Wimperis, Vice-President, for his help in obtaining the Air Ministry grants, to Mr. Fairey, Captain Acland and Mr. Handley Page for the S.B.A.C. grants, and to Mr. F. R. Simms for the S.M.M.T. grants. It has already been recorded under the Endowment Fund that without these grants the Society would not be able to go forward with its policy of keeping its members in touch with the latest scientific and technical information, and the Council here emphasise what has been said in the paragraph on the Endowment Fund.

Library

For the seventh year in succession the Council have to thank Mr. J. E. Hodgson, the Honorary Librarian, for the time he has given to the Library, and for acting in connection therewith as the Society's representative at the Council meetings of the National Central Library for Students and the Association of Special Libraries and Information Bureaux.

The Council have to thank Mr. Hodgson, too, for the loan of many of his valuable prints to the International Colonial and Maritime Exhibition at Antwerp, which enabled the Society to stage an extremely interesting and representative exhibit.

During the year many slides, photographs and books were presented to the library by members and firms, and full acknowledgment has been given in the Annual Summary of the Society's activities published in the Journal for December, 1930.

The experiment of opening the library on Saturday afternoon has proved a success. On alternate Wednesday afternoons the library has been closed for the meeting of the Council of the Society of British Aircraft Constructors, who have generously paid all the expenses of keeping the library open on Saturday afternoons.

Lecture Programme

A full list of the lectures delivered before the Society, and the principal lectures delivered before the Branches, was given in the Journal for December, 1930. In addition, the following lectures have been delivered or arranged for during the remainder of the present session:—

Lectures before the main Society.

January 8th.—" Some Aspects of the Design and Construction of Sea-going Aircraft." Mr. A. Gouge, B.Sc., A.F.R.Ae.S.

January 22nd.—" Deck Flying." Squadron-Leader W. R. D. Acland, D.F.C., A.F.C.

January 29th.—" The Development and Construction of Sailplanes and Gliders." Herr A. Lippisch. (Joint meeting with the British Gliding Association).

February 26th.—" Meteorological Aspects of Gliding and Soaring." Captain F. Entwistle, B.Sc. (Joint meeting with the British Gliding Association).

March 12th.—" Night Air Mails." Captain Carl Florman. (Joint meeting with the Institute of Transport).

March 19th.—" Research in the Berlin Technische Hochschule." Dr. W. Hoff.
March 31st.—" Injection, Ignition and Combustion in High-speed Heavy-oil Engines." Dr. S. J. Davies, Ph.D., M.Sc., M.I.Mech.E., and E. Griffen, M.Sc., A.M.I.Mech.E. (Joint meeting with the Institution of Automobile Engineers and other Societies).
April 16th.—" Aircraft Noise." Dr. A. H. Davis.
April 30th.—" Aerodynamics of Sails." Dr. Manfred Curry.
May 14th.—" The Metal-clad Airship." Mr. Carl Fritsche.

Lectures before the Branches.

January 8th.—Yeovil Branch. " Aircraft Production Methods in America." Mr. R. A. Bruce, F.R.Ae.S.
January 16th.—Manchester Branch. " The Practical Lubrication of Aircraft Engines." Messrs. Shell Mex, Ltd.
January 22nd.—Yeovil Branch. " Model Aeroplanes." Mr. W. Rigby.
January 29th.—Yeovil Branch. " Machining and Working of Stainless Steel." Mr. R. Waddell.
January 30th.—Hull and Leeds Branch. " Gliding and Soaring." Colonel the Master of Sempill, A.F.C., F.R.Ae.S.
February 3rd.—Manchester Branch. " The Evaporative Cooling of Aero Engines." Mr. Ellor.
February 5th.—Bristol Branch. " American and Canadian Aviation." Captain J. Laurence Pritchard, Hon.F.R.Ae.S.
February 5th.—Yeovil Branch. " Westland Wapiti in Australia." Squadron-Leader C. T. Anderson, D.F.C.
February 12th.—Gloucester and Cheltenham Branch. " Magnetos." Mr. Schobel.
February 12th.—Yeovil Branch. " Spinning." Mr. S. Scott-Hall, A.F.R.Ae.S.
February 19th.—Gloucester and Cheltenham Branch. " Heat Treatment of Steels." Mr. A. L. Williams, B.Sc., A.M.I.Mech.E.
February 19th.—Yeovil Branch. " Lay-out and Equipment of Service Aircraft." Squadron-Leader R. B. Sorley, D.S.O., D.F.C.
February 24th.—Manchester Branch. " Machine Tools." Messrs. Alfred Herbert, Ltd.
February 26th.—Gloucester and Cheltenham Branch. " Motor Fuels and Modern Methods of Testing." Messrs. Anglo-American Oil Co.
February 26th.—Yeovil Branch. " Latest Aircraft Instrument Developments." Major C. J. Stewart, O.B.E., F.R.Ae.S.
February 27th.—Hull and Leeds Branch. " Aircraft Light Alloys." Mr. H. Sutton, M.Sc., A.F.R.Ae.S.
March 5th.—Gloucester and Cheltenham Branch. " Mechanical Testing of Aircraft Materials." Mr. L. W. Nethercott, A.R.Ae.S.I.
March 12th.—Yeovil Branch. " Metals." Mr. W. K. Norton, A.I.D.
March 27th.—Hull and Leeds Branch. " The Flying of High-speed Seaplanes." Squadron-Leader A. H. Orlebar, A.F.C.

Wilbur Wright Memorial Lecture

The Wilbur Wright Memorial Lecture for 1930 was delivered before a distinguished audience on 30th May, 1930, in the Lecture Hall of the Royal Society of Arts, by Mr. H. R. Ricardo, F.R.S., F.R.Ae.S., M.I.A.E., Assoc.M.Inst.C.E., on " The Development and Progress of the Aero Engine." The lecture was printed in the Journal for December, 1930.

The Annual Council Dinner was held immediately following the lecture, and a full list of those present was printed in the December, 1930, Journal.

Students' Section

The Students' Section during 1930 continued to show a very satisfactory increase in membership and activity. Many of these students are coming from the Royal Air Force, and the Council wish to thank all those officers concerned for the long view they have taken of the future careers of those in the Royal Air Force who will ultimately have to take up civilian appointments. A number of students are preparing for the Associate Fellowship examination. The Council feel that ultimately every student should aim at becoming a member of one of the technical grades of the Society, as membership of such a grade is of definite value when applying for any appointment.

In addition to the lectures announced in the December, 1930, Journal the following have been given or arranged for before the Students' Section:—

January 27th.—" The Future Popularity of Aviation." Mr. J. N. Richmond.
February 10th.—" High-speed Air Flow." Mr. S. G. Hooker.
February 24th.—" The Design and Manufacture of Aluminium Alloy Castings." Mr. R. McVie.
March 3rd.—" The Contribution of the Glider to Aerodynamics." Mr. W. S. Coleman.
March 10th.—" Seaplane Floats." Mr. R. C. Passmore.
April 28th.—" Airships." Mr. E. Wieser.

The Honorary Secretary of the Students' Section is Mr. T. Tanner, to whose energy and enthusiasm during the past year much of the increasing success of the Students' Section is due.

Branches

The first branch of the Society was formed in Coventry in 1925, and since then new branches have been formed and have been doing excellent work. The Council feel that, difficult though the conditions are sometimes for forming and carrying on branches, the experience of the past five years has proved definitely that branches are of the utmost possible value to sow the early seeds of interest in technical progress and to enable those in the industry and those interested in aviation to meet together and discuss aviation problems. The Council wish to encourage the formation of further branches in every possible way, and are prepared to offer all assistance within their power both for the actual formation of a branch and its carrying on.

To the Chairmen, Honorary Secretaries and Committees of the present branches the Council offer their sincere congratulations for the very excellent work they have been doing. The list of lectures read before the branches, printed in these Council reports and in the summaries of the year's activities, is eloquent testimony in itself of the immense amount of energy which has so willingly been expended by the committees and officers of the branches.

During the year a new branch was formed at Gloucester and Cheltenham under the Chairmanship of Mr. Folland and Honorary Secretaryship of Mr. L. W. Nethercott. The branch has already 140 members and there is every prospect of the number increasing and the branch becoming a flourishing one.

Following the Secretary's visit to Canada a new branch is being formed in Montreal and further branches will probably be formed in other centres in Canada during the coming year.

It is with great regret that the Council have to record the dissolving of the Halton Branch on account of Service reasons. The success of the branch was due almost entirely to Captain Latimer Needham, the Honorary Secretary, and the Council hope that the immense energy which he showed during the existence of the branch will be made use of in other directions.

The following is a list of Branches and their addresses:—

COVENTRY: Hon. Sec., F. Meadows, A.F.R.Ae.S., "Llangstone," Jobs Lane, Coventry.

YEOVIL: Hon. Sec., V. S. Gaunt, A.M.I.Ae.E., Westland Aircraft Works, Yeovil.

HULL AND LEEDS: Hon. Sec., G. B. Fenton, A.F.R.Ae.S., "Fairview," Brough, E. Yorks.

MANCHESTER: Hon. Sec., F. Paxton, A.M.I.Ae.E., "Cyntra," Poplar Road, Didsbury, Manchester.

BRISTOL: Hon. Sec., C. W. Tinson, F.R.Ae.S., M.I.Ae.E., Russell House, Russell Grove, Westbury Park, Bristol.

OXFORD: Hon. Sec., Wing-Comdr. R. M. Hill, M.C., A.F.C., F.R.Ae.S., Oxford University Air Squadron, Manor Road, Oxford.

GLOUCESTER AND CHELTENHAM: Hon. Sec., L. W. Nethercott, Esq., A.R.Ae.S.I., "Bearswood," Glencairn Park Road, Cheltenham.

AUSTRALIA: Hon Sec., J. V. Connolly, Esq., A.R.Ae.S.I., Macleay House, 16, College Street, Melbourne, Australia.

CAMBRIDGE UNIVERSITY AERONAUTICAL SOCIETY: Hon. Sec., Wight Boycott, Esq., Scoope House, Cambridge.

President

At a meeting of Council held on 24th June, 1930, Mr. C. R. Fairey, M.B.E., F.R.Ae.S., was elected President of the Society for the year October, 1930-September, 1931. Mr. Fairey delivered his Presidential Address, "The Growth of Aviation" on Thursday, 9th October, 1930.

During the three months (October-December, 1930) in which he has held office Mr. Fairey has thrown himself into the work of the Society with characteristic energy, and by his personal appeal on behalf of the Endowment Fund has begun to build a secure financial foundation for the Society, the value of which is already being felt.

Journal

The Journal is now recognised as being the leading and most authoritative publication of its kind throughout the world. The growth of its influence is reflected in the growth of its sales to non-members of the Society. There is an increase of 1,930 over the record year of 1929. The sale of the Journal is world-wide, and an analysis of the destination of Journals reveals the fact that there is hardly a country in the world where the Journal does not circulate.

Finance

The Balance Sheet and Income and Expenditure Account of Aerial Science Ltd. are published in this issue of the Journal. The form in which the accounts are drawn up shows an excess of income over expenditure for the year under review of £1,637 4s. 3d. The Council wish to point out that the excess is entirely due to generous donations which have been received, amounting in all to £1,823 18s. 5d. Deducting the donations, which are in no sense permanent sources of income, but are entirely dependent upon the goodwill of the donors, there is an actual loss on the year of £186 14s. 2d. This loss is less than has been the case for some years. Last year it was £862, and the year before £600. The improvement has largely been due to economies effected in salaries, by a new printing contract, and by increased subscriptions. The Council feel that every effort should be made to make the Society really self-supporting and that, in view of the progress that is being made, this happy result can be arrived at in a very short time if every member uses all his influence to help, and interests those who are not at present members.

AERIAL SCIENCE, LIMITED

Balance Sheet,

Dr.	£	s.	d.	£	s.	d.
To *Share Capital*—						
Authorised—						
20 Shares of 1/- each and 999 Shares of £1 each	1000	0	0			
,, *Issued*—						
19 Shares of 1/- each, fully paid				0	19	0
,, *Sundry Creditors*				734	1	0
,, *Amount owing to Endowment Fund—as per contra*				62	4	7
,, *Subscriptions Received in Advance*				119	14	0
,, *Donations received in advance*				1022	2	6
,, *Carnegie U.K. Trust Grant for Purchase of Books*—unexpended balance				34	11	5
,, *Endowment Fund*—						
Balance at 31st December, 1929	1077	5	0			
Add—Donations received	38	2	1			
Entrance Fees received during year	150	3	0			
				1265	10	1
,, *Surplus*						
Reserve Fund—						
Balance as at 31st December, 1929	3553	0	9			
,, *Income and Expenditure Account*—						
Balance as at 31st December, 1929	1557	11	9			
Add—Excess of Income over Expenditure for year to date	1637	4	3			
	3194	16	0			
				6747	16	9
				£9986	19	4

We report to the Members that we have examined the Books of the Society, and have obtained is properly drawn up so as to exhibit a true and correct view of the state of the Society's affairs, of the Society.

3, Frederick's Place, Old Jewry, London, E.C.2.

Income and Expenditure Account

Dr.	£	s.	d.
To Office Rent, Heating, Lighting and Insurance	425	6	1
,, Salaries	1032	15	0
,, Printing and Stationery	363	1	8
,, Postages, &c....	213	19	7
,, Office Expenses	178	14	7
,, Meetings	184	3	6
,, Journals, Pamphlets, Etc....	610	11	10
,, Library Expenses	46	4	1
,, Audit Fee	18	18	0
,, Prizes	42	10	0
,, Dinners and Receptions	59	5	6
,, Subscriptions Written off	96	19	9
,, Examination Expenses	19	1	0
,, Secretary's Canadian Visit	200	0	0
,, Excess of Income over Expenditure for Year, carried to Balance Sheet	1637	4	3
	£5128	14	10

(The Royal Aeronautical Society).

31st December, 1930.

Cr.	£	s.	d.	£	s.	d.
By *Office Furniture, Printed Books, Bindings, Old Prints, etc.*, as at 31st December, 1929	915	14	6			
Less proportion of Expenditure received from Carnegie Grant ...	465	8	7			
				450	5	11
,, *Stock of* JOURNALS, *etc.*				672	12	8
,, *Stock of Stationery*				13	0	0
,, *Sundry Debtors, including Subscriptions owing*				178	1	2
,, *Investments at Cost*—						
£5552 14s. 3d. 5% War Stock, 1929/47	5565	4	9			
£1648 3s. 9d. 4½% India Stock, 1958/68	1500	0	0			
(Market value at 31st December, 1930, £7164 1s. 2d.)				7065	4	9
,, *Endowment Fund*—						
£1532 0s. 11d. 3½% Conversion Stock at cost	1184	18	3			
(Market value at 31st December, 1930, £1254 6s. 6d.)						
Cash at Bank	18	7	3			
Amount owing by General Funds, as per contra	62	4	7			
				1265	10	1
,, *Cash at Bank and in Hand*—						
At Bank...	333	10	0			
In Hand...	8	14	9			
				342	4	9
				£9986	19	4

all the information and explanations we have required. We are of opinion that such Balance Sheet according to the best of our information and the explanations given to us and as shown by the Books

(Signed) PRICE, WATERHOUSE & CO.

for the Year Ending 31st December, 1930.

Cr.	£	s.	d.	£	s.	d.
By Annual Subscriptions				2913	1	3
,, Interest on Investments (*Less* Tax)	320	8	2			
,, ,, ,, Deposit	5	8	5			
,, ,, ,, Endowment Fund (*Less Tax*)	35	6	9			
				361	3	4
,, Donations				1772	2	9
,, ,, for Library				51	15	8
,, Legal Expenses recovered from Aeronautical Trusts, Ltd.				30	11	10
				£5128	14	10

AERONAUTICAL

Balance Sheet,

Dr.	£ s. d.	£ s. d.
To *Share Capital*—		
Authorised—		
40 Shares of 1/- each	2 0 0	
Issued—		
21 Shares of 1/- each	1 1 0	
Less—Calls in arrear	1 1 0	
,, *Pilcher Memorial Fund*—		
Capital Account	99 14 0	
Surplus on Income Account	25 8 8	
		125 2 8
,, *Usborne Memorial Fund*—		
Capital Account	109 2 5	
Surplus on Income Account	13 5 5	
		122 7 10
,, *Herbert Akroyd Stuart Fund*—		
Capital Account	688 19 0	
Surplus on Income Account	34 5 0	
		723 4 0
,, *R.38 Memorial Fund*—		
Capital Account	978 3 10	
Surplus on Income Account	185 19 10	
		1164 3 8
,, *Edward Busk Memorial Lecture Fund*—		
Capital Account	449 6 1	
Surplus on Income Account	69 14 9	
		519 0 10
,, *Wilbur Wright Memorial Fund*—		
Capital Account	1298 9 9	
Surplus on Income Account	81 18 11	
		1380 8 8
,, *Simms Gold Medal Fund*—		
Capital Account	250 0 0	
Less—Deficiency on Income Account	1 14 6	
		248 5 6
		£4282 13 2

We report to the Members of Aeronautical Trusts, Ltd., that we have examined the above explanations we have required. We are of opinion that the Balance Sheet is properly drawn up December, 1930, according to the best of our information and the explanations given to us and as

3, Frederick's Place, Old Jewry, London, E.C.2.
2nd March, 1931.

TRUSTS, LTD.

31st December, 1930.

Cr.	£ s. d.	£ s. d.
To *Pilcher Memorial Fund*—		
£115 6s. 10d. 5 % War Stock, 1929/47, at cost	116 5 0	
Cash at Bank	8 17 8	
		125 2 8
,, *Usborne Memorial Fund*—		
£113 5 % War Stock, 1929/47, at cost	114 11 1	
Cash at Bank	7 16 9	
		122 7 10
,, *Herbert Akroyd Stuart Fund*—		
£683 1s. 0d. 5 % War Stock, 1929/47, at cost	698 19 0	
Cash at Bank	24 5 0	
		723 4 0
,, *R.38 Memorial Fund*—		
£1048 11s. 2d. 5 % War Stock, 1929/47, at cost	1098 18 10	
Cash at Bank	65 4 10	
		1164 3 8
,, *Edward Busk Memorial Fund*—		
£284 4s. 2d. 5 % War Stock, 1929/47	284 4 2	
£245 Metropolitan Railway 4 % Debentures at cost	200 1 11	
	484 6 1	
Cash at Bank	34 14 9	
		519 0 10
,, *Wilbur Wright Memorial Fund*—		
£1047 6s. 7d. 3½ % Conversion Stock, at cost	800 0 0	
£550 Canadian 4 % Stock, at cost	531 10 9	
	1331 10 9	
Cash at Bank	81 18 11	
	1413 9 8	
Less—Amount owing to Aerial Science, Ltd.	33 1 0	
		1380 8 8
,, *Simms Gold Medal Fund*—		
£287 16s. 1d. India 4½ % Stock, 1958/68, at cost	250 0 0	
Cash at Bank	15 0 6	
	265 0 6	
Less—Amount owing to Aerial Science, Ltd.	16 15 0	
		248 5 6
		£4282 13 2

Balance Sheet with the books of the Company and have obtained all the information and so as to exhibit a true and correct view of the state of the Company's affairs as at 31st shown by the books of the Company.

PRICE, WATERHOUSE & CO.

AERONAUTICAL

INCOME & EXPENDITURE ACCOUNTS

Pilcher

RECEIPTS.

	£	s.	d.
To Balance carried forward	25	8	8
	£25	8	8

Usborne

To 1930 Award	5	0	0
,, Balance carried forward	13	5	5
	£18	5	5

Herbert Akroyd

To Sundry Expenses	0	4	0
,, 1930 Award	68	0	0
,, Balance carried forward	34	5	0
	£102	9	0

R.38

To 1930 Award	26	5	0
,, Balance carried forward	185	19	10
	£212	4	10

Edward Busk

To 1930 Award	21	0	0
,, Balance carried forward	69	14	9
	£90	14	9

Wilbur Wright

To 1929 Award	50	0	0
,, 1930 ,, ...	50	0	0
,, Balance carried forward	81	18	11
	£181	18	11

Simms Gold

To 1929 Award	16	15	0
,, Sundry Expenses	0	4	0
	£16	19	0

TRUSTS, LTD.

FROM 17TH MAY, 1929 (DATE OF INCORPORATION) TO 31ST DECEMBER, 1930

Memorial Fund

PAYMENTS.

	£ s. d.
By Balance on Income Account taken over from previous Trustees	16 15 8
,, Interest on Investments (gross)	8 13 0
	£25 8 8

Memorial Fund

By Balance on Income Account taken over from previous Trustees	9 15 11
,, Interest on Investments (gross)	8 9 6
	£18 5 5

Stuart Fund

By Balance on Income Account taken over from previous Trustees	51 4 6
,, Interest on Investments (gross)	51 4 6
	£102 9 0

Memorial Fund

By Balance on Income Account taken over from previous Trustees	133 12 1
,, Interest on Investments (gross)	78 12 9
	£212 4 10

Memorial Lecture Fund

By Balance on Income Account taken over from previous Trustees	57 15 0
,, Interest on Investments (*less* Tax)	32 19 9
	£90 14 9

Memorial Fund

By Balance on Income Account taken over from previous Trustees	112 5 10
,, Interest on Investments (*less* Tax)	69 13 1
	£181 18 11

Medal Fund

By Interest on Investments (*less* Tax)	15 4 6
,, Balance carried forward	1 14 6
	£16 19 0

Honorary Solicitor

The Council wish to place on record the great services which have been rendered to the Society by Mr. Lawrence Wingfield, M.C., D.F.C. (Associate), the Honorary Solicitor. During the year Mr. Wingfield has advised the Council on a number of important legal questions, including the formation of Aeronautical Trusts, Ltd., to take over the various Trust Funds and Award Funds administered by the Society. The formation of Aeronautical Trusts has now been completed.

Honorary Treasurer

For the fourth year in succession the Council have to acknowledge the debt they owe to Major D. H. Kennedy, F.R.Ae.S., the Honorary Treasurer and Chairman of the Finance Committee. Major Kennedy has had constantly under review the Society's finances, and has put forward many suggestions and schemes which have proved of great value.

Honorary Accountant

The Council record for the third year in succession the value of the work done and advice given by Mr. Norman Smith, the Honorary Accountant. Mr. Smith has placed his time freely at the disposal of the Society during the past year, particularly in connection with certain Income Tax problems which are now under consideration.

Staff

The Council wish every member to realise that the real work of the Society comes upon the Staff, that though the Council direct policy and initiate schemes for the welfare of the Society, the carrying out of these schemes is in the hands of the staff. The progress which has been made during the past few years is an indication of the efficiency of the staff. The staff is smaller than those of other comparable societies, and although the work and income of the Society has increased very rapidly during the past few years, the salaries have actually decreased during that time.

During the year Captain Pritchard paid a visit to Canada. During his absence the work of carrying on the Society fell upon the President, Colonel the Master of Sempill, and the Honorary Treasurer, Majorj D. H. Kennedy, both of whom kept in constant touch with the staff and directed the Secretarial work of the Society, which owes them a great debt for the great amount of time and energy they devoted in the absence of the Secretary. The Council wish to record the very excellent work Miss Jarvis, Miss Todd and Miss Voice did during Captain Pritchard's absence, and the way they have loyally assisted him throughout the year.

CORRESPONDENCE

Editor of the Journal,

Royal Aeronautical Society.

RE JET PROPULSION.

Dear Sir,—There are one or two points I should like to raise in connection with the article on "Jet Propulsion" by Dr. Richardson, B.A., Ph.D., D.Sc., in the January issue of the JOURNAL.

The experiments described do not indicate an induced velocity in fluid external to the jet, due to the entraining of the external air by the jet. This is possibly due to the low velocities employed, but this entraining must occur, as shown by the false readings obtained with the impulse plate method of testing the performance of turbine nozzles, when special steps are not taken to prevent the jet fluid from entraining air from the side of the plate opposite from the jet, and thereby causing a low pressure distribution on that side. The steam jet air pump should also be quoted as an example of this phenomenon.

In this connection the two following simple experiments were performed by myself. In each case a car tyre pump was used to produce the jet.

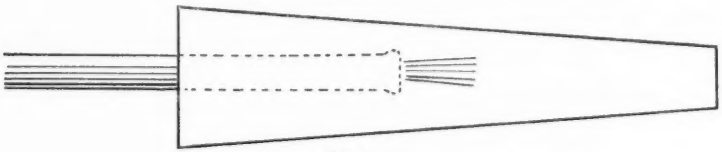

FIG. 1.

In the first, the "jet" was placed in a paper cylinder as illustrated and a source of smoke (a cigarette) was held in the position shown. On slowly depressing the piston of the pump, the smoke was drawn through the tube by the jet; proving conclusively that a jet induces a velocity in the air external to the jet. This effect was also obtained to a smaller degree without the paper cylinder. It is clear, therefore, that the pressure distribution over neighbouring surfaces is affected, and in the case of a jet situated at the apex of a cone as shown in Fig. 2 (as it probably would be in the case of aircraft),

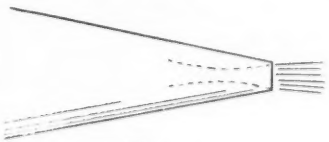

FIG. 2.

the pressure distribution will be such as to constitute a drag. This fact must be allowed for in the estimation of the performance of a jet.

In the other experiment, a hollow cone was substituted for the cylinder. The arrangement is shown in Fig. 3.

The cone was free to move. On pushing down the pump piston, the cone moved vigorously in the direction opposite to the jet, that is from right to left in the figure. It should be added that this effect was only obtained

when the nozzle was inserted about or more than one-third the length of the cone. If it were inserted less than this, the cone was blown off, as would be expected.

The behaviour of the cone is very surprising to watch, and clearly demonstrates the existence of a low pressure distribution over the inside surface of the cone as a result of the entraining of external air by the jet. This experiment indicates a method of neutralising the drag induced by a jet.

Dr. Richardson does not indicate the type of compressor used in his experiments, nor does he say whether the temperature of the jet was measured, and since this will affect the density, and further, since the mass discharge appears to have been computed by integrating the jet velocities, the density is very important.

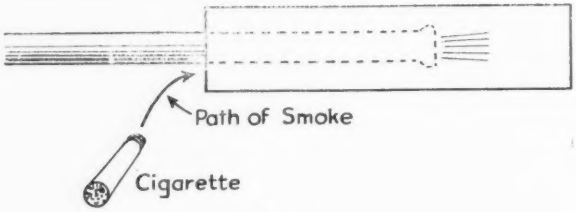

FIG 3.

Dr. Richardson states at the foot of Page 31, " . . . . while a compressor would not give sufficient power in relation to its weight, we are led to the combustion of solid or liquid fuel as the only practical solution, which means in practice that the jet propeller must be a rocket."

This is a surprising statement, because when the propelled object depends on the product of jet velocity and rate of mass ejection for its thrust, then either the jet velocity must be very high, or the rate of mass ejection must be large. In the first case the jet is very inefficient, and in the second, enormous quantities of " rocket mixture " must be carried for very short flights.

On the other hand, if the external air is to be taken in and expelled with increased velocity, only the means of supplying the energy to the expelled fluid must be carried, namely fuel and the mechanism. The power required by the compressor is of course in proportion to the work it does on the air in increasing its velocity, and if the right type of compressor is selected the weight would not be excessive. The turbo-compressor driven by an engine is clearly one method of applying jet propulsion, and the turbo-compressor is very light in proportion to the work it has to do, principally because it is a high speed mechanism. It also has an enormous capacity in proportion to its size. For example, a turbo-compressor with a 9 in. diameter rotor and peripheral speed of about 1,000 ft./sec. has a capacity of 9 - 12 cubic feet of free air per second.

The ability of a turbo-compressor to deal with such large volumes means that to produce a given thrust quite low jet velocities will suffice, and consequently there is hope of reasonable efficiency.

Another method of applying jet propulsion which appeals to the writer, is the incorporating of the jet as the final expansion in a thermal cycle, as illustrated in the Pressure-Volume Diagram, Fig. 4. Where *AB* represents the compression of air, *A F H B* the work of compression, *BC* heat addition, *CD* expansion through mechanism designed to perform the work of compression, and *DE* the final expansion through the propelling jets.

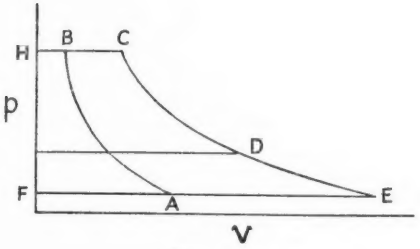

FIG. 4.

The writer believes that this incorporation of the jet as part of a heat engine would result in a much lighter mechanism than the combination of a normal engine and turbo-compressor.

Yours faithfully,
J. WHITTLE.
Flying Officer, R.A.F.

January 24th 1931.

REVIEWS

Jane's All the World's Aircraft, 1930

Edited by C. G. Grey. Sampson Low, 42/- net.

This is the twentieth year of issue of the most useful record of aircraft development published in any country. A history of the development of aircraft since that day in December, 1903, when the Brothers Wright made the first controlled flight in a power-driven heavier-than-air craft, comparable with Mr. J. E. Hodgson's comprehensive history of earlier years, is now badly needed. When it comes to be written one of the most valuable sources of information will be the work started by the late F. T. Jane, and now so admirably carried on by Mr. C. G. Grey.

The year under review has been a quiet one, but every section of the book shows an increase. One predicts that it will not be many years before it must either be curtailed in the immense range it covers, or be issued in more than one volume. The analysis of civil aviation is very thorough and extraordinarily useful and the editor is to be congratulated upon the fullness of it, despite the difficulties of obtaining it. The more difficult information is to obtain, however, the more worth while it is. All praise and no criticism is not good for publisher or editor, so one might add that in the list of Aeronautical Publications in Great Britain appears no notice of *Aircraft Engineering* and the price of the *Journal* is given as 2/6 monthly instead of 3/6, and the price of *Airways* as 6d. instead of 1/-.

Aviation of To-day. Its History and Development

J. L. Nayler and E. Ower. 208 illustrations. Warne & Co., 15/- net.

The names of Mr. J. L. Nayler, Secretary of the Aeronautical Research Committee, and Mr. E. Ower, Assistant Secretary, on the cover of a book, are a sufficient guarantee that that book will be worth reading. Few better collaborators could have been found. The book is a vast survey, an orderly survey, a mass of digested information on aviation which will prove palatable to most. It begins with the Bible " the way of an eagle in the air " and ends with the Royal Air Force Pageant at Hendon. Between such an excellent beginning and

ending there is collected so much of interest that it requires twenty-one columns of a closely printed index to help one to find one's way about. The book is not only one which will make a popular appeal, but one which will be refreshing to the technical expert to read. Father may buy it for his boy, but it is father who will read it first. Son will delight in the illustrations, father in the text. This is not only a book for those interested in aviation, it is one to interest the rising generation. The reviewer predicts " Aviation of To-day " will become a classic.

The Law of Aviation

E. D. Nokes, LL.D., and H. P. Bridges, LL.D. Chapman & Hall, 12/6 net.

The law of the air is rapidly growing. It is and must necessarily be for some time a growth of experience. Although there is much legislation to prevent the breaking of the aerial peace, much more will follow the actual breaking of that peace in years to come. The international convention on aerial navigation has already been amended on many occasions and these amendments involve, often, changes in national laws.

In this book the state of the international law has been stated and how it affects the English law. The law of aviation is very fully foot-noted with references, and the list of cases cited is already imposing. The first half of the book deals with the law in peace and the second half that of law in war. The regulations for peaceful flying are much more definite than those for military flying.

The authors are to be congratulated not only upon the presentation of their work, but upon its general arrangement, which makes it a book of easy reference. It is one which can be thoroughly recommended.

Aluminium Facts and Figures

The British Aluminium Company Ltd.

This is a series or data sheets in book form issued by the British Aluminium Company. The rapidly increasing use of light alloys in aircraft construction makes this book of very definite value, as in its 140 pages is collected a mass of useful information on aluminium and its alloys in all forms, weights, strengths, sizes, manufacture, heat treatment, machining, riveting, etc. There are in addition a number of useful tables, physical properties of various metals, etc. It is the pocket encyclopedia of aluminium and its alloys and should be in every designer's office.

How to Become an Air Pilot

R. L. Preston. Sampson, Low, Marston & Co., 3/6 net.

Mr. R. L. Preston is to be congratulated on a very readable and very useful book. The book deals with the necessary steps which must be taken to become a pilot. It does not teach flying. Its five chapter headings, " General Information," " The Royal Aero Club Certificate and Air Ministry A Licence," " The Technical Examination," " Information for the Private Owner," and " Notices to Airmen of special interest," give completely the scope of the book.

Here is outlined the qualifications for becoming a pilot, the cost, the time it takes to learn, where flying is taught, where equipment may be obtained, etc. In Chapter III. a very full series of likely questions and answers is given, and in the following chapter many details of use to the private owner, as for example the cost of flying, cost of insurance, etc. (Incidentally there occurs the sentence " Do not class insurance with the Income Tax and Railway Companies, both of whom it is considered perfectly legitimate to swindle if possible," one which might be cut out of the next edition.) In its ninety pages there is packed a mine of information of the utmost use to the private owner and prospective pilot.